Saph Pani

Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India

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Database of baseline data for study sites

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1 Chennai

1.1 Site specific background knowledge

1.1.1 Synthetic site description

Chennai is the largest city in South India located in the eastern coastal plains. Water supply to the Chennai city is met by reservoirs and by groundwater. Most of the groundwater is pumped to the city from the well fields located in the Araniyar and Korttalaiyar River (A-K River) catchment north of Chennai (

Figure 1). The total surface water area of the A-K River catchment is around 6282 km^2, divided between Andhra Pradesh and Tamil Nadu. Severe pumping from these regions for supply to the Chennai city and for local irrigational needs has also resulted in seawater intrusion. The Minjur well field lies nearest to the coast (9 km) and it is hydraulically connected with the sea. This well field has been intruded by seawater up to a distance of 15 km since 1969 due to extensive extraction of groundwater for agricultural, industrial and domestic uses for prolonged periods. The average rainfall on the basin is 7-9 billion m3 /year, which corresponds to 950-1250 mm/year. Even though the annual rainfall is moderate, extreme cases of very high daily rainfall were recorded in past in the Chennai basin. Severe rainfall during short periods of time combined with high percentage of impervious areas in this region is the major source of flooding. Thus, the Chennai region on one hand is affected by floods and on the other by severe shortage of water.

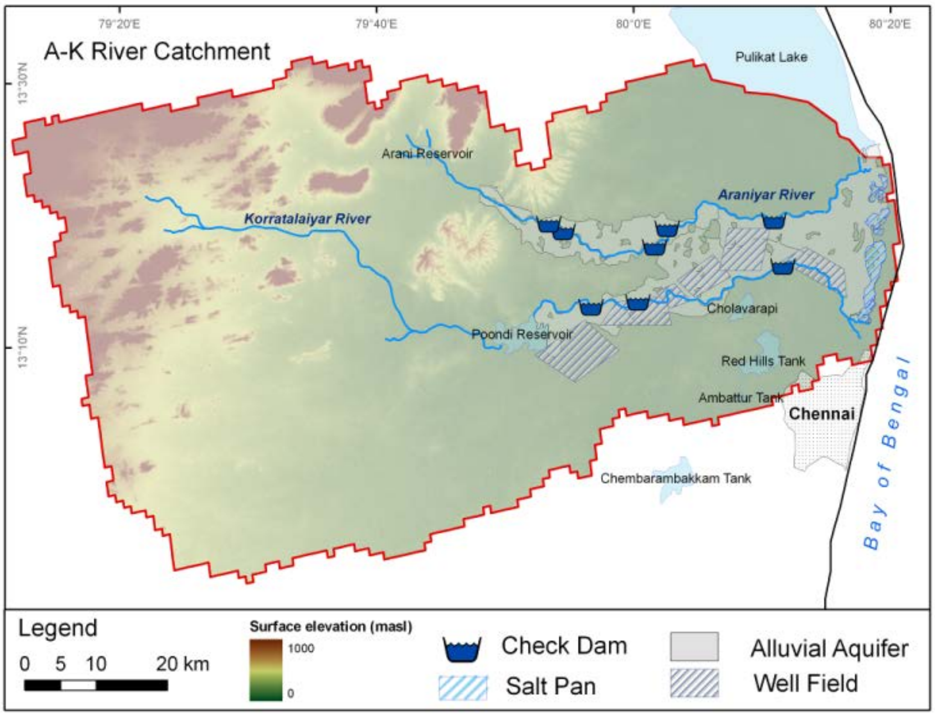

Figure 1 Overview of A-K River catchment

The north east (winter) monsoon is the more significant, as it replenishes the surface reservoirs and also recharges the groundwater. Water is stored in reservoirs and used cautiously. They are virtually empty before the next annual rainfall. The shortfall in surface water storage systems is met from groundwater resources. About one third of the water demand is met by groundwater from several well fields about 30 km north of Chennai.

The city has two major rivers namely Adyar and Cooum. Both these rivers usually carry sewage and only heavy rain events can get these rivers flushed. The city itself has very meagre groundwater resources due to very little rainfall recharge. Most of the inner basin surface water comes from three reservoirs, namely Redhills, Poondi and Cholavaram. Maximum storage capacity of these three reservoirs is around 210 Mm^3. The storage capacity from these three reservoirs would last only for half a year. The inter basin transfer consists of Veeranam lake (235 km away) and Kandaleru dam (175 km away) and groundwater is abstracted from the well fields north and north west of Chennai. The water supplied by Chennai Metro Supply and Sewage Board does not cover the demand and the accumulated gap is at the end of a year around 200 Mm^3 (20 %). This gap is met by private groundwater abstraction and by the commercial water companies.

The main objectives for the case study site in Chennai is to undertake a comprehensive assessment of MAR for coping with sea-water intrusion and groundwater overexploitation and to develop recommendations and a management plan for implementing MAR systems in Chennai that utilize excess monsoon water to counteract seawater intrusion.

1.1.2 Previous projects

Balakrishnan (2008) investigated the hydrogeology and hydrochemistry of the Chennai region. The author identified salinity ingress as one of the main groundwater related problems in the region.

Ganesan and Thayumanavan (2009) developed a 3D MODFLOW/MT3D flow and transport model for the coastal aquifer north/northeast of Chennai. The model was calibrated by monthly average inflows, outflows and piezometric head contours for the period from 1976 – 82 and simulated the movement of saltwater for the period from 1983 – 96. The calibrated model was used for seven scenarios with various groundwater abstraction rates and injection rates for the period from 1997 – 2020. According to the authors, the fresh-saltwater interface, expressed as the 1000 mg/L isoline, will be under a worst case scenario approximately 11 km from the coast. Reduction in groundwater withdrawals and/or the injection of freshwater was found to reduce the seawater movement toward the land. The model does not account for density dependent flow and the hydraulic heads used for calibration were temporally and spatially averaged. However, the optimal pumping and injection rates stated in this study may provide useful information for an improved and extended numerical model.

Sundaram et al. (2008) investigated the vulnerability of the coastal aquifers in Pondicherry (approx. 120 km south of Chennai) in terms of seawater intrusion using GIS methods and evaluated the effects of MAR techniques on the dynamics of the freshwater-seawater interface in the region. Runoff potential was calculated by Soil Conservation Service from the US department of agriculture along with curve number tables. The effect of MAR on seawater intrusion was evaluated using groundwater flow rate equation from Raudkivi & Callander (1976). The authors found out that the runoff potential in the region is sufficient for MAR to counteract seawater intrusion.

Anuthaman (2009) studied the groundwater augmentation by flood mitigation in Chennai region using HEC HMS and HEC RAS. Elango (1992) carried out a hydrogeochemical study and mass balance modelling of multilayered aquifers in Chennai region.

1.2 Data collection and management

1.2.1 Data available at the onset of the project

Table 1 Data available at the onset of the project for modeling at Chennai site at the onset of Saph pani

Sl.No	Data
1.	Topographical map – 1:25000
2.	Geology map
3	Geomorphology map
4.	Groundwater level – from 1993 to 2007
5.	Meterology (Climate and Rainfall – 2009 to 2010)
6.	Aquifer parameters
7.	Landuse map
8.	Lithology

1.2.2 Data requirements for modeling

Table 2 Modelling data required for Chennai site

Type	Description
River courses and profiles	Maps, cross sections and shapefiles
Relevant structures along the rivers (weirs, check dams)	Measures and locations, optionally operating management rules
Groundwater observation wells	Locations, measure frequency and available measure period of groundwater tables
Reservoir Data	Water-Volume Curves, operating data, water levels
Surface water levels of rivers	Locations, measure frequency and available measure period of surface water tables
Surface water extractions	Amount, location, and dynamic information (which month how much extraction)
Surface water levels of rivers	Locations, measure frequency and available measure period of surface water tables
Soil and Geological Profiles at boreholes	Kf-Values, locations and depths
Digital Terrain Model	
Geological maps	Spatial distribution of main aquifers, k-values, thicknesses
Extractions of groundwater	Amount, location, and dynamic information (which month how much extraction)
Groundwater recharge information	Used as input for the groundwater model, can optionally be derived from actual meteorological data
Isolines of interpolated groundwater levels	For calibration
Salinity observation	Location of measurement, date, for GW-Measurements also depth of measurement

Table 3 Supporting Data for Chennai site (also important for Rainfall-Runoff modelling)

Type	Description
Topographical maps	
Remote Sensing data	
Soil Map	For upper groundwater model layer
Landuse map	In case spatially distributed groundwater recharge has to be calculated

Refined flow and transport model for site operation

Environmental tracer data for the calibration of the flow of the pilot site

- diurnal/seasonal temperature fluctuations
- stable isotopes ($\delta^{18}O$, $\delta^{2}H$)
- Chloride, Bromide...

Hydrochemical and geochemical data for the assessment of refreshening effects on saline/brackish aquifer chemistry

- Hydrochemistry
- main ions
- pH, dissolved oxygen, temperature, Eh
- Aquifer characteristics
- ion exchange capacity
- grain size distribution
- Organic carbon content

1.2.3 Status of data collection at M12

Initially, the data required for modelling such as rainfall, borehole lithologs and long term groundwater level observations were collected from various departments of the Government of Tamil Nadu, India. A base map was prepared from toposheets obtained from Survey of India (Figure 2). In order to improve the topographical information, Differential Global Positioning System (DGPS) survey was carried out at about 45 locations (Figure 3). The study area has a maximum elevation of 133 m amsl (above mean sea level). Geology map of the study area was derived from the geological map procured from Geological Survey of India (GSI) (Figure 4). To understand the subsurface geological formation of the area, lithologs were collected from Chennai Metropolitan Water Supply and Sewerage Board (MWSSB). The groundwater level data from January 1996 to December 2011 was collected from Public Works Department (PWD). Also, rainfall data from January 1985 to December 2011 in 6 raingauge stations (Table 4) were collected from PWD.

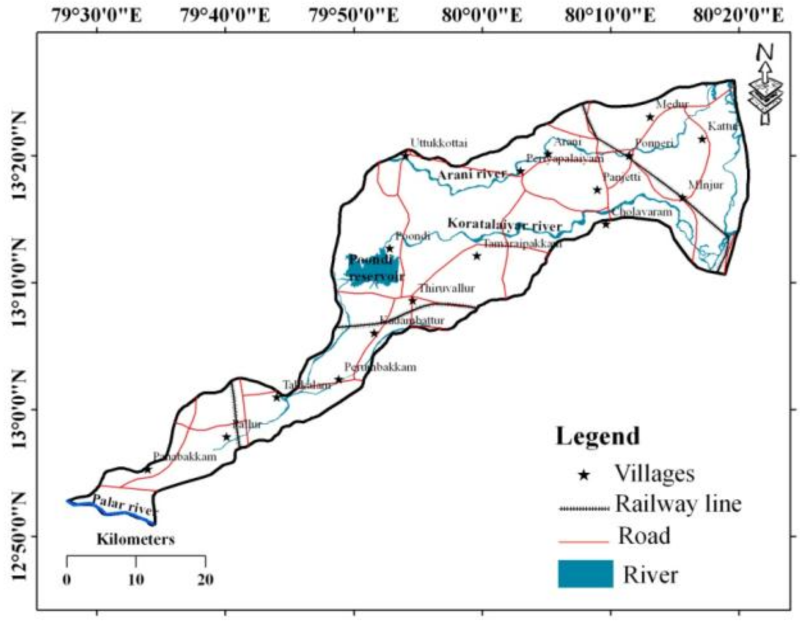

Figure 2 Base map of the Chennai study area

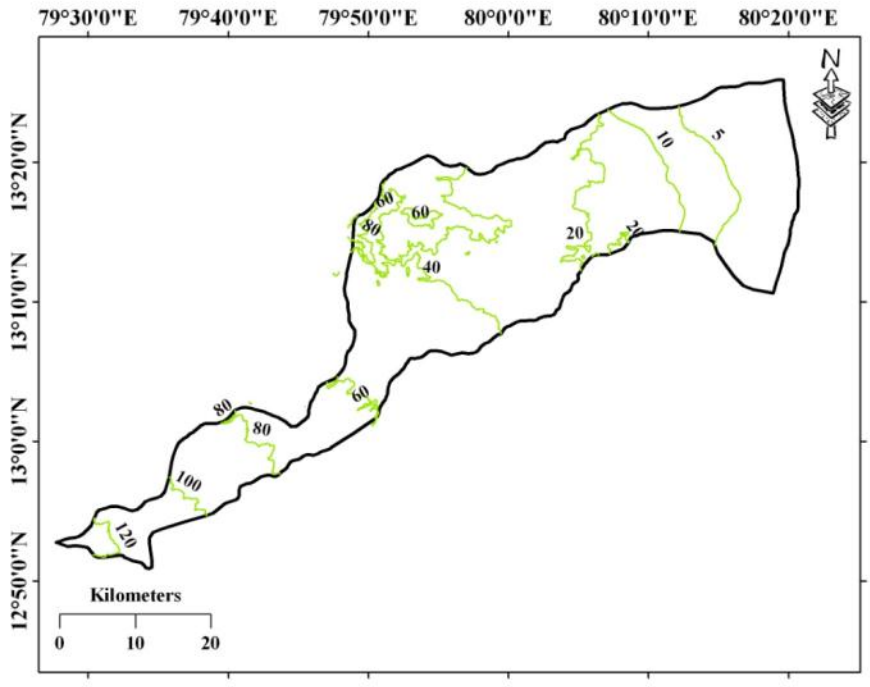

Figure 3 Topographical elevation (m) of the Chennai study area

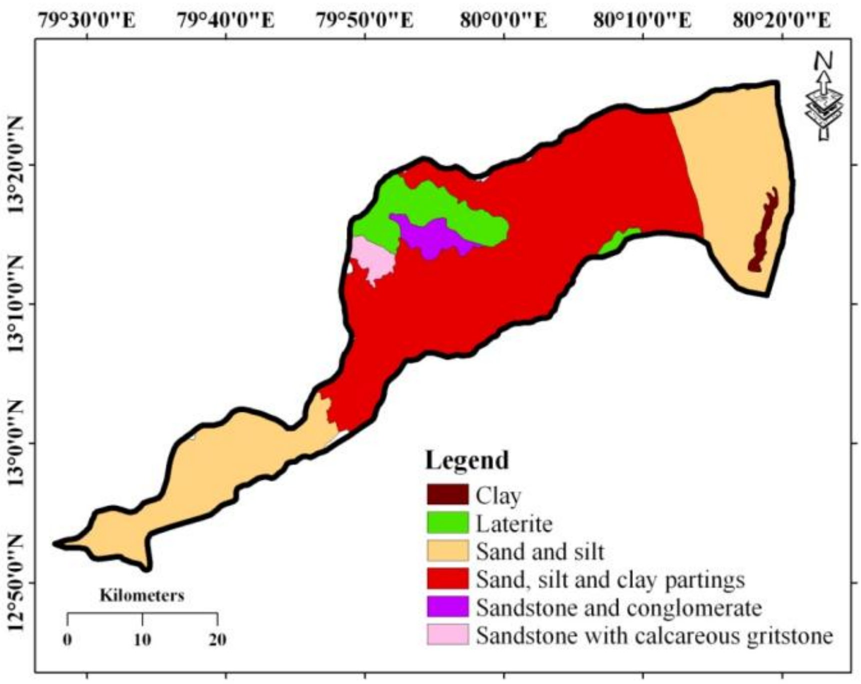

Figure 4 Geology of the Chennai study area

Table 4 Location of rainfall stations

Station name	Latitude	Longitude
Keshavaram	13°02'00"	79°46'00"
Perumalpet	13°18'30"	80°03'00"
Tiruvallore	13°08'00"	79°55'00"
Uthukottai	13°20'00"	79°54'00"
Ponneri	13°19'00"	80°12'00"
Vallur Anicut	13°16'00"	80°15'00"

1.2.4 Data management

please complete with information on the established data base (GIS if relevant), data base structure and contents, show GIS layers in 1-2 figures

Various spatial maps were prepared in Arc GIS 9.3 environment. Thus the date required for groundwater modelling is managed using this software. As of now the following geospatial maps have been prepared:

1. Base map
2. Topography map
3. Geology map
4. Drainage map

5. Landuse map
6. Geomorphology map

1.3 Site-specific literature list

1.3.1 Publications (journals, conferences….)

Balakrishnan , T. (2008) DISTRICT GROUNDWATER BROCHURE CHENNAI DISTRICT, TAMIL NADU , Government of India , Ministry of Water Resources , Central Ground Water Board , South Eastern Coastal Region ,

Ganesan , M., Thayumanavan, S. (2009) Management Strategies for a Seawater Intruded Aquifer System , Journal of Sustainable development, Vol. 2, No 1

Sundaram, Dinesh, G.., Ravikumar and D.Govindarajalu (2008), Vulnerability assessment of seawater intrusion and effect of artificial recharge in Pondicherry coastal region using GIS, Indian Journal of Science and Technology, Vol. 1, No. 7, 1-7

Raudkivi AJ and Callander RA (1976) Analysis of ground water flow. Edward Arnold (Publishers) ltd, Old Woking, Surrey, London.

Sathish, S. and Elango, L. (2011) Groundwater quality and vulnerability mapping of an unconfined coastal aquifer. Journal of Spatial Hydrology, Vol. 11(1), 18-33.

Sathish, S., Elango, L., Rajesh, R., and Sarma V.S. (2011) Application of Three Dimensional Electrical Resistivity Tomography to Identify Seawater Intrusion, Earth Science India, Vol. 4(1), 21-28.

Sathish, S., Elango, L., Rajesh, R., and Sarma V.S. (2011) Assessment of seawater mixing in a coastal aquifer by high resolution electrical resistivity tomography. International Journal of Environmental Science and Technology, 8 (3), 483-492.

Senthilkumar, M. and Elango, L. (2011) Modelling the impact of a subsurface barrier on groundwater flow in the lower Palar River basin, southern India. Hydrogeology Journal, 19(4), 917-928.

Sivakumar C. and Elango, L. (2010) Application of solute transport modeling to study tsunami induced aquifer salinity in India. Journal of Environmental Informatics, 15(1), 33-41.

Elango, L. and Manickam, S.(1987) Hydrogeochemistry of the Madras aquifer, India - Spatial and temporal variation in chemical quality of groundwater. Geol.Soc. of Hong Kong Bull. No. 3, pp. 525-534.

Elango, L. and Manickam, S., (1986) Groundwater quality of Madras aquifer: A study on Panjetti-Ponneri-Minjur area. Indian Geog. Joul., 61: 41-49.

Elango, L. and Ramachandran, S. (1991) Major ion correlations in groundwater of a coastal aquifer. J. Indian Water Reso. Soc., 11: 54-57.

Gnanasundar. D and Elango. L (1998), Groundwater quality of a coastal urban aquifer, Journal of Environmental Protection, Vol.18, pp. 752-757.

Gnanasundar. D and Elango. L (1999) Groundwater quality assessment of a coastal aquifer using geoelectrical techniques, International Journal on Environmental Hydrology, Vol. 6, pp 21-33.

Gnanasundar.D and Elango.L (2000) Groundwater Flow modeling of a coastal aquifer near Chennai City, India, Joul. of Indian Water Reso. Soc., Vol. 20, 4/162-171.

Senthil Kumar, M., Gnanasundar, D. and Elango,L.(2001) Geophysical studies in determining hydraulic characteristics of an alluvial aquifer, Journal of Environmental Hydrology, Vol.15/9, pp. 1-8.

Punit Kumar Bhola (2012): Modelling of Ungauged Araniyar–Korttalaiyar River Basin, Chennai, India. Master Thesis, Brandenburg University of Technology, Cottbus

1.3.2 Other accessible data (web, reports…)

http://www.chennaimetrowater.tn.nic.in/public/lake.htm

daily lake level data from the reservoirs

daily rainfall measurements

2 Delhi site

2.1 Site specific background knowledge

2.1.1 Synthetic site description

Transport and transformation processes of Nitrogen species are studied in an urban aquifer in New Delhi (India). The study site is located close to the Oklah barrage in the south eastern part of New Delhi (Figure 5). Here, the Yamuna River is heavily polluted by poorly treated and untreated urban waste water and the existing drinking water production wells close to the river produce bank filtrate of low quality. The high concentration of nitrogen (mostly ammonia) makes the abstracted groundwater unfit for drinking water purposes and most of the production wells are abandoned. Nonetheless, the groundwater is used by urban dwellers and small scale farmers. Before distribution, the bank filtrate is treated for nitrification, in order to oxidize the ammonium present. The current plant is designed to treat 4 mg/L of ammonium – however, it is predicted that in future up to 10 mg/L of ammonium are likely to occur. Different options to sustain drinking water quality are to be evaluated in WP1 such as improving source water or enhancing the extensive post-treatment.

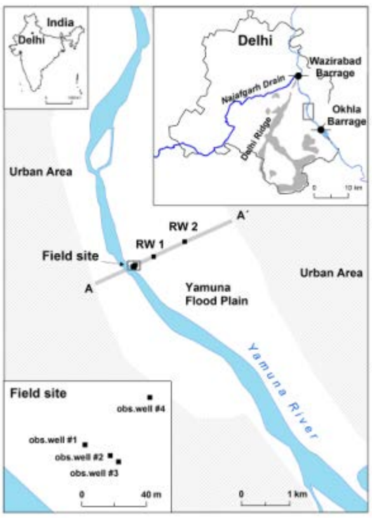

Figure 5 Location of field site during the TECHNEAU project. RW = Ranney Well, horizontal filter well

WP5 activities focus on the transport behaviour of nitrogen species under the given environmental conditions. Column experiments will be used to evaluate transformation and transport processes of nitrogen under changing redox conditions. Specific cation exchange capacity, organic carbon content and other sediment properties (grain size distribution, effective porosity) will be determined. Based on the column experiments, various abstraction schemes and prediction of changes in redox conditions and the resulting ammonium and nitrate concentrations in pumped water in NCT Delhi will be evaluated. Already existing numerical models (2D, flow and transport) will be further developed in order to verify and predict nitrogen fate and transport. The reaction network will be established after the identification of the main geochemical reaction such as anammox, nitrification, denitrification, redox reactions (Figure 6). Based on the available data, a 1D model will be developed. The calibrated and validated model will demonstrate the likely effect of different remediation strategies on groundwater quality. Different abstraction schemes or the improvement of river water quality will be tested during scenario modelling.

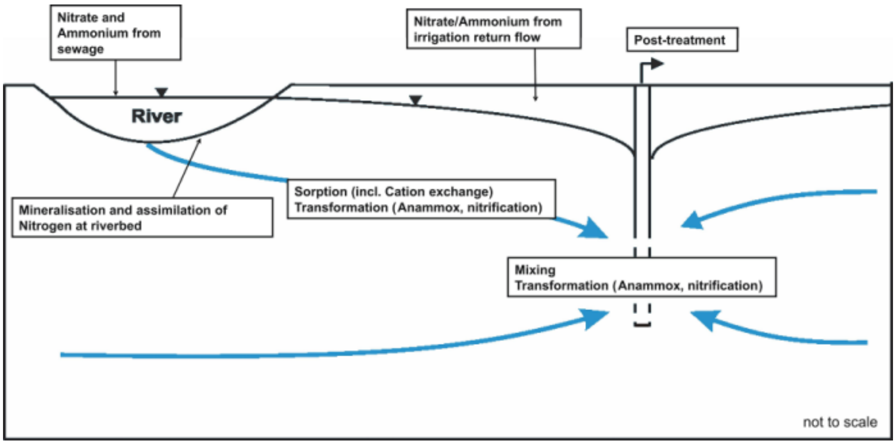

Figure 6 Sketch of main geochemical processes of N-species during anoxic subsurface passage.

2.1.2 Previous projects

Project acronym/name: TECHNEAU

Duration: from 2006 to 2010

Framework: FP6

Coordination/partnership : Partner

What was done: At the central Delhi field site the impact of highly contaminated surface water infiltration on the urban aquifer systems was investigated. At this field site, RBF takes place because of dominant losing river conditions due to large groundwater abstraction. Fluctuations of the hydraulic head in combination with a conservative tracer (chloride) and a retarded tracer (heat) were measured, evaluated and modelled to determine (i) infiltration rates and (ii) groundwater travel times, (iii) to perform a sensitivity analysis and (iv) to calculate a water budget for the flood plain aquifer.

Website or information on the web : www.techneau.org

2.2 Data collection and management

2.2.1 Data available at the onset of the project

During drilling of the observation wells, three lithological units were encountered: i) the younger alluvial, ii) the older alluvial, and iii) the quartzitic hardrock. The younger alluvium is composed of Holocene sediments of the Yamuna floodplain, deposited close to the present course of the river. This unit consists mainly of grey, medium-sand fluviatile deposits interbedded with calciferous gravel size concretion, locally known as kankar. This upper aquifer unit extends down to 12 m below ground level at the river and shows an increasing thickness to the east (up to 30 to 40 m below ground level). The coefficient of hydraulic conductivity (k-value) is estimated by grain size analysis with 29 - 33 m/d (Table 5). The younger alluvium was deposited upon a series of variable thickness of older alluvium. The older alluvium is composed of Tertiary sediments which are outcropping to the west of the present course of the Yamuna. This unit consists mostly of yellow to brown silt and is more consolidated than the upper floodplain sediments. Mica is accessory or absent, and in places the fine sand is interbedded with layers of fine to medium sand.

At a depth of 38 m below ground level, the Precambrian metamorphic hardrock (Aravalli formation forming the Delhi Ridge) was encountered. In the upper part of this formation these metamorphites are weathered, but owing to the low permeability of this quartzitic unit, it is considered to be an aquitard.

Table 5 Parameters (d_{10}, d_{60}) determined from grain size distribution of the aquifer at different depths and calculated coefficients of hydraulic conductivity (k) according to Hazen 1893 and Beyer 1964

Depth (mbgl)	d_{10} (mm)	d_{60} (mm)	Hazen 1893 k (m/d)	Beyer 1964 k (m/d)
3	0.15	0.39	33.3	29
6	0.15	0.4	33.3	28.9
13	0.06	0.38	5.3	3.9
20	0.02	0.1	0.6	0.5
30	0.01	0.08	0.1	0.1
40	0.002	0.08	0.01	0.002

Hazen

$k = C * d_{10}$^2 (only valid for d_{10}>0.06 mm)

C = 0.7 + 0.03 * T / 86.4 (T=26 °C)

Beyer

$k = g/v*C_b*d_{10}$^2 (only valid for d_{10}>0.06 mm)

g=gravity constant; v=kinematic viscosity of water

$C_b=0.0006*\log(500/U)$

$U=d_{60}/d_{10}$

Coefficients of hydraulic conductivities were calculated according to Hazen 1893 and Beyer 1964 under consideration of the temperature-dependent kinematic viscosity of water. Owing to the limited validity of the Hazen and Beyer method, the k-value was also estimated by small-scale pumping tests and slug/bail tests (not shown here). According to the k values obtained by the grain size distribution (Table 1) the model was subdivided into three zones of hydraulic conductivity. The k values were iteratively calibrated by trial-and-error to the measured tracer curves. Therefore, values were slightly higher than those derived from grain size distribution. The upper alluvium was attributed to k = 36 m/d. As a first approximation, it was assumed that the hydraulic conductivity was isotropic for the younger alluvium aquifer, but it was determined iteratively that an anisotropy factor of Kh/Kv = 10 gives the best fit. The older alluvium was attributed uniformly with a horizontal k = 5 m/d and the vertical conductivity was set to 0.05 m/d owing to the occurrence of small silt/clay layer. The bottom of the model corresponds to the quartzitic hardrock and was set inactive.

The upper alluvium is unconfined, which means that the effective porosity is equal to the storage coefficient. The effective porosity was estimated to be 25% (ne = 0.25). The storage coefficients were considered to decrease with depth.

2.2.2 Data requirements for modeling

Geochemical analysis of aquifer material (CEC, Fe compounds, Corg etc.) for column experiments (contaminated aquifer material & fresh water)

2.2.3 Status of data collection at M12

Main focus of the Delhi case study is the investigation of fate and transport of N-species during underground passage. A first sampling campaign was conducted in March/April 2012. Ammonium concentrations of the Yamuna River and flood plain aquifer are shown in Figure 7. Ammonium concentrations (Figure 7) are 14 mg/l in the surface water. In the flood plain aquifer, ammonium concentrations up to 12 mg/l can be found in the sampling points closest to the river; with increasing distance to the river the concentration in the groundwater decreases. In Ranney well P4, situated about 2 km from the riverbank, the ammonium concentration is 0.4 mg/l.

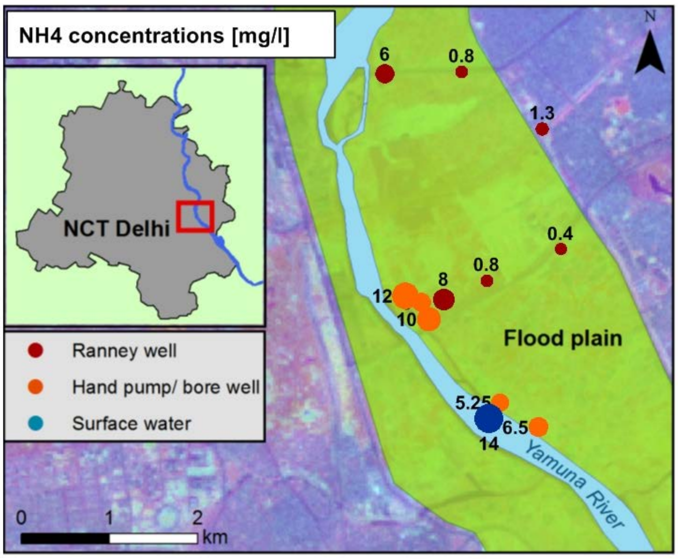

Figure 7 Ammonium concentrations in surface-/groundwater at Yamuna flood plain in Delhi in March/April 2012

During the field campaign in March/April 2012 also sediment samples were taken from different depths (0 - 4 m) at five locations. The sampling locations are situated at various distances to the Yamuna River. The sample material includes material from the unsaturated zone as well as material from the top of the saturated zone. Different sediment properties (grain size distribution, Corg, Cation exchange capacity) of the samples are analysed and column experiments will be carried out. A drilling permission was received from the Delhi Jal Board and the drilling campaign was completed in Oct.2012. About 40 sediment samples from different depths in the saturated zone have been sent to Berlin. A second sampling campaign of surface-/groundwater is currently in progress. Details of primary data acquisition are shown in Table 6.

Table 6 Status of primary data acquisition at the Delhi site

Data type	Parameters	Data status
Soil properties 21 samples, unsaturated zone	Grain size distribution Cation exchange capacity Ignition losses	completed completed completed
Soil properties 40 samples, saturated zone	Grain size distribution Cation exchange capacity Ignition losses	in progress in progress in progress
Levelling of observation wells, abstraction well against mean sea level	River stage of Yamuna River, selected hand pumps, Ranney well and observation wells in meters above sea level	in progress
Monitoring of water quality	Inorganics, NH_4, NO_2, NO_3, HS^-,	1st campaign completed (March/April 2012) 2nd campaign in progress (October - November 2012)
Monitoring of water levels	2 pressure transducer in newly constructed observation wells	Installed in October 2012
Extraction of N-species by ion exchange columns, method adapted from Silva et al. 2000	N^{15}-isotopes	1st campaign completed (March/April 2012) 2nd campaign in progress (October - November 2012)

All water samples were filtered on site by 0.2 µm membrane filters. A method adapted from Silva et al. 2000 was used to extract inorganic N-species for isotope analysis. The filtrate was passed through a pre-filled, pre-rinsed Poly-Prep cation exchange resin columns by gravity flow. The columns hold a certain exchange capacity and to prevent potential incomplete sorption of ammonium-N the columns were not saturated.

2.2.4 Data management

All existing data are available in raw format, excel files or GIS format.

2.3 Site-specific literature list

2.3.1 Publications (journals, conferences….)

Lorenzen, G., Sprenger, C., Taute, T., Pekdeger, A., Mittal, A., Massmann, G., (2010) Assessment of the potential for bank filtration in a water-stressed mega city (Delhi, India) Environmental Earth Sciences, Volume 61, Number 7H, 1419-1434, DOI: 10.1007/s12665-010-0458-x

Pekdeger, Lorenzen, Sprenger (2008) Preliminary report on data of all inorganic substances and physicochemical parameters listed in the Indian and German Drinking Water Standards from surface water and groundwater at the 3 (+1) field sites. TECHNEAU Integrated Project, European Commission, deliverable D5.2.1; available: http://www.techneau.org/index.php?id=120

Silva, S.R, Kendall, C., Wilkison, D.H., Ziegler, A.C, Chang, C.C.Y., Avanzino R.J. (2000) A new method for collection of nitrate from fresh water and the analysis of nitrogen and oxygen isotope ratios, Journal of Hydrology 228, 22–36

3 Haridwar RBF site

3.1 Synthetic site description

Haridwar is one of the most important Hindu pilgrimage sites in the world. In this context, on a single auspicious day, as many as 10 million pilgrims are estimated to bathe in the Ganga River and Upper Ganga Canal (Figure 8), which serve as a source of the bank filtrate abstracted by the 22 RBF wells (Figure 9). During such religious gatherings, not only does the water supply of Haridwar have to effectively meet extreme surges in demand, but it also has to cater to the constant demand of the permanent population of > 225,000 persons (Census of India, 2011). This, and the demographic fact that by 2011 the permanent urban population of Haridwar had increased by around 63 % since 2001 (Census of India, 2011), are important considerations for the management of the Haridwar's water supply.

Figure 8 Haridwar town, UGC (foreground) and Ganga River (background).

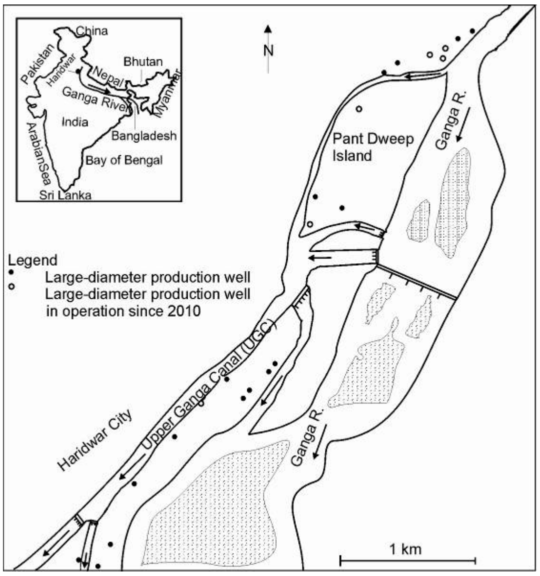

Figure 9 RBF wells in Haridwar.

Haridwar is the administrative headquarters of the Haridwar district (2360 km^2). The district experiences a moderate sub-tropical to humid climate, with the main seasons being summer, monsoon and winter. The average annual rainfall in Haridwar district is 1174 mm (recorded at the weather station in Roorkee, 30 km SW of Haridwar), out of which 84 % is received during monsoon and 16 % occurs during non-monsoon (CGWB, 2009). The CGWB (2009) states the presence of a multi-layered aquifer system occurring under unconfined, semi-confined and confined conditions, separated by thick clay layers. It also states that the groundwater chemical parameters are well within permissible limits and suitable for drinking (IS 10500, 1991) and irrigation purposes. Studies regarding the efficiency and sustainability of RBF commenced on Pant Dweep Island (Figure 9) in 2005 (Dash et al., 2010; Sandhu et al., 2010, 2011). These studies report the unconfined aquifer on Pant Dweep to comprise fluvial deposits to a depth of 20 m below ground and sediments ranging from fine sand and silt to medium sand and gravel. The deposit is overlain by Holocene river boulders. The aquifer can be described as a single-layer system which is in direct hydraulic contact with the river and the canals surrounding Pant Dweep. These studies report that bank filtrate abstracted from a production well on Pant Dweep Island, when compared with Ganga River water, showed significant removal of total coliforms, E. Coli, turbidity and organics for travel time of 77–126 days. The abstracted water from all the RBF wells in Haridwar only requires disinfection by chlorination, and provides safe drinking water even when facing high variations in water demand (such as during the Kumbh and Ardh Kumbh Melas) and during monsoons (Sandhu et al., 2011).

However, following one of the severest monsoons in North India and as reported by the Central Water Commission of India, the Ganga River rose to an unprecedented level of 296 m above sea level on 19 September 2010, inundating the ground surface around the nearby wells. The water in the wells became turbid and for over 48 hours, the wells were operated continuously and all the abstracted water was discharged back into the river until the turbidity disappeared. It is believed that the sharp increase in turbidity was the result of the floodwater percolating down the well shaft. In WP5, site data from Haridwar will be used to develop a conceptual model as a base for formulating suggestions for monitoring and operation during floods.

Drinking water production by riverbank filtration: The permanent population of the entire urban agglomeration of Haridwar that includes the outgrowths (suburban areas) was 310,582 persons according to the 2011 census, out of which 225,235 persons permanently reside in the main or core city area (Census of India, 2011). The bank filtrate abstracted from 22 large-diameter (10 m) caisson wells is supplied solely within the limits of the main city (Figure 9). Being one of the most important Hindu pilgrimage sites in the world, Haridwar has a “floating” population of around 200,000 persons who reside temporarily within the main city in religious retreat locations (“Ashrams”) and hotels, and an additional 400,000 – 500,000 persons (mainly pilgrims) visit the main city every day (Uttarakhand Jal Sansthan, 2012). Accordingly, the production from the 22 RBF wells accounts for nearly 50 % (> 43,000 m^3/day) of the total drinking water demand of the entire population within the main city. Groundwater abstraction through vertical production wells ("tube" wells) covers the remainder of the drinking water demand in the main city.

3.2 Previous projects

Project acronym/name: Indo-German Riverbank Filtration Network (RBFN)

Duration: from 01.09.2008 to 31.12.2010

Framework: German Federal Ministry of Education and Research (BMBF) funding, within its programme "India and Germany – Strategic Partners for Innovation".

Coordination/partnership: HTWD (coordinator). Partners: UJS, water company Stadtwerke Düsseldorf AG, IITR and Cooperation Centre for Riverbank Filtration (CCRBF)

What was done: As a component of the RBFN project, a groundwater flow model using PMWIN was constructed for Pant Dweep Island (Figure 9) to obtain an improved understanding of the groundwater flow pattern and to determine the travel-time and flow-path of bank filtrate on Pant Dweep (Sandhu et al., 2010). The model was calibrated for steady-state conditions. Transient simulations were conducted for a one year period covering the main seasons of monsoon, post-monsoon (winter) and pre-monsoon (summer) to understand the travel-time and flow-path of bank filtrate under changing surface water flow conditions over the one year period around Pant Dweep (changes in water levels). Due to the extremely sparse data-set, a validation of the simulated groundwater heads was not possible.

3.3 Data collection and management

3.3.1 Data available at the onset of the project

Relatively detailed geological and hydrogeological data exists ONLY for Pant Dweep island in Haridwar (Figure 9). Lithological information of the aquifer has been derived from the borehole logs of two monitoring wells, pumping tests have been conducted on three existing wells on the island. Sieve analyses of the Upper Ganga Canal (UGC) and Ganga river bed material has been conducted at various locations around Pant Dweep Island. Water levels have been measured on and around Pant Dweep Island on various reference day measurements. This information is summarised in the form of an extended abstract of a paper presented at the IAH conference in Krakow in 2010 (Sandhu et al., 2010) and is already being used for an existing groundwater flow model of Pant Dweep island. Information on the water quality is presented in the article Dash et al. (2010). However for the region in Haridwar to the north of Pant Dweep Island where seven RBF wells are located, and for the region to the south of Pant Dweep Island where 11 RBF wells are located between the Upper Ganga Canal and Ganga River, only the datum (benchmark in metres ASL) to measure water level for each well, the well depth and GPS coordinates are available. The borehole logs for some handpumps in the area are also available on paper.

3.3.2 Data requirements for modeling

Typical data requirements for PMWin / Visual Modflow, see Annex “RBF site parameter list”

3.3.3 Status of data collection at M12

The following categories of data were measured and documented for the Haridwar site:

a) Water levels: Regular manual groundwater and surface water level measurements (since 2011) have been documented in an excel file.

b) Distance of water-line of river to river bank has been documented for certain reference-day measurements

c) Water quality data consisting of physico-chemical parameters, major ions and pathogenic indicators have been documented into an excel file.

d) A subsurface cross-section has been constructed for the RBF site on Pant Dweep Island using borehole-logs available for the monitoring wells MW1 and MW2 at IW18

e) Hydraulic conductivities have been determined for the RBF site from pumping tests and for the riverbed material from grain-size distribution analyses.

Water quality : Due to the relatively low population residing upstream of Haridwar along the Ganga river (compared to downstream), and the sufficient discharge and gradient of the river, the main water quality parameters of concern for RBF in Haridwar are pathogens and turbidity (Table 7). During monsoon, the total and faecal coliform counts and turbidity of the Ganga by the RBF wells in Haridwar are significantly higher than during non-monsoon periods. Dash et al. (2010) report that bank filtrate abstracted from production well 18 on Pant Dweep Island, when compared to raw Ganga River water, showed 2.5-log removal of total coliforms, 3.5-log removal of faecal coliforms, 0.7-log removal of turbidity in the non-monsoon period (November 2005–June 2006) for the shortest travel time of 84–126 days at a minimum distance of 115 m, and 4.7-log removal of total coliforms, 4.4 log removal of faecal coliforms, 2.5-log removal of turbidity and 1.0-log removal for organics as measured by UV absorbance during the monsoon period (July–September 2006) for the shortest travel time of 77–126 days. Other studies on RBF in Haridwar (Sandhu et al., 2011) have revealed bank filtrate having very low dissolved organic carbon content of < 1 mg/L under aerobic conditions, an arsenic concentration of less than 0.01 mg/L and other trace metals and major ions below the Indian Standard IS 10500 (1991) limit.

Table 7 Values of relevant parameters and their removal during RBF in Haridwar

Parameter	Range of concentration [Min. – Max. (mean [n])]			Proportion of bank filtrate [%]	Removal [% or Log_{10} for pathogens & turbidity]	Reference
	Surface water	Observation well(s)	Production well			
Total coliform [MPN/100 mL]	4,300 – 230,000	<2 – 23	<2 – 93	> 70 %	2.5 (non-monsoon) – 4.7 (monsoon)	Dash et al., 2010
Faecal coliform [MPN/100 mL]	1,500 – 93,000	0 – 23	0 – <2		3.5 (non-monsoon) – 4.4 (monsoon)	Dash et al., 2010
Turbidity [NTU]	1 – 200	0.1 – 13.1	0.2 – 0.6		0.7 (non-monsoon) – 2.5 (monsoon)	Dash et al., 2010
n = number of samples	22	22	11	-	-	-

3.3.4 Data management

The data used is summarized in Table 8.

Table 8 Data used for preparing the groundwater flow model for Haridwar

Category	Information about
Well data	location, diameter, depth, groundwater levels and partly discharge, running hours
River data	water levels, cross-sections, discharge (Ganga river)
Borehole-log data	Large-diameter caisson well (IW) 18 (Pant Dweep), vertical filter Well (TW) Bhupatwala, TW Mayapur
Climate data	minimum & maximum temperature, relative humidity, wind velocity, rainfall (2004 to 2008 for Jwalapur)
GIS data	well, river and borehole-log locations, DEM
Literature data	Hydraulic conductivity of the riverbed (Ganga River at Bhimgoda Barrage, UGC, NSC) and model layers

In Figure 10 the discharge of the Ganga river, measured in the downstream area of Bhimgoda Barrage is shown. This clarifies as an example the surface water hydrology of Haridwar region, influenced especially by rainfall during monsoon-season. Based on the numerical groundwater modelling floods and their influence on flow patterns and travel times will be analysed to possibly optimise the operating conditions of the RBF wells.

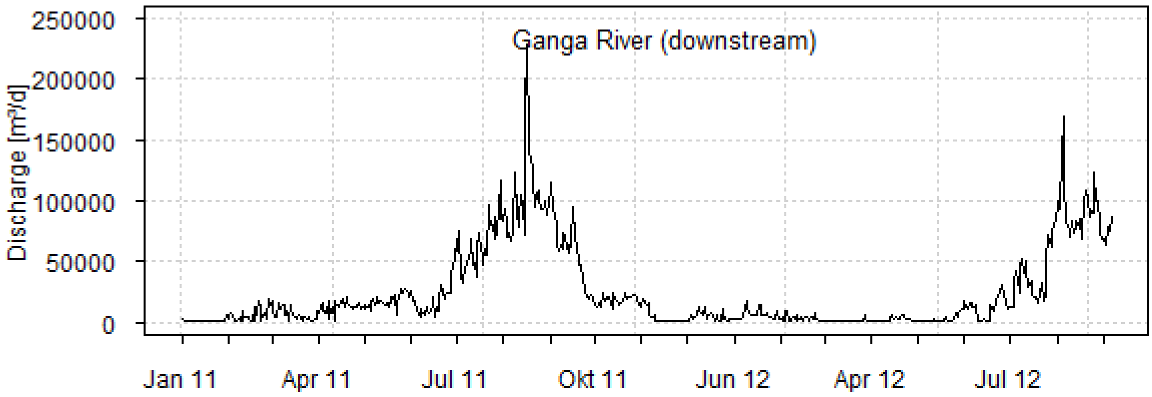

Figure 10 Discharge of Ganga River (upstream area of Bhimgoda Barrage)

To define the spatial extend of the model area and a sitemap for the numerical modelling a map was prepared in ArcGIS (Figure 11). The map includes the locations of the large-diameter caisson RBF wells, borehole-logs and rivers as well as the elevation within the study area. According to the borehole-log data the thickness of the aquifer was derived for the northern, middle and southern part of the study-site. Based on this, the DEM-data and the known elevation of the wells a input file for the numerical groundwater model, which is defining the surface and below surface area, was prepared.

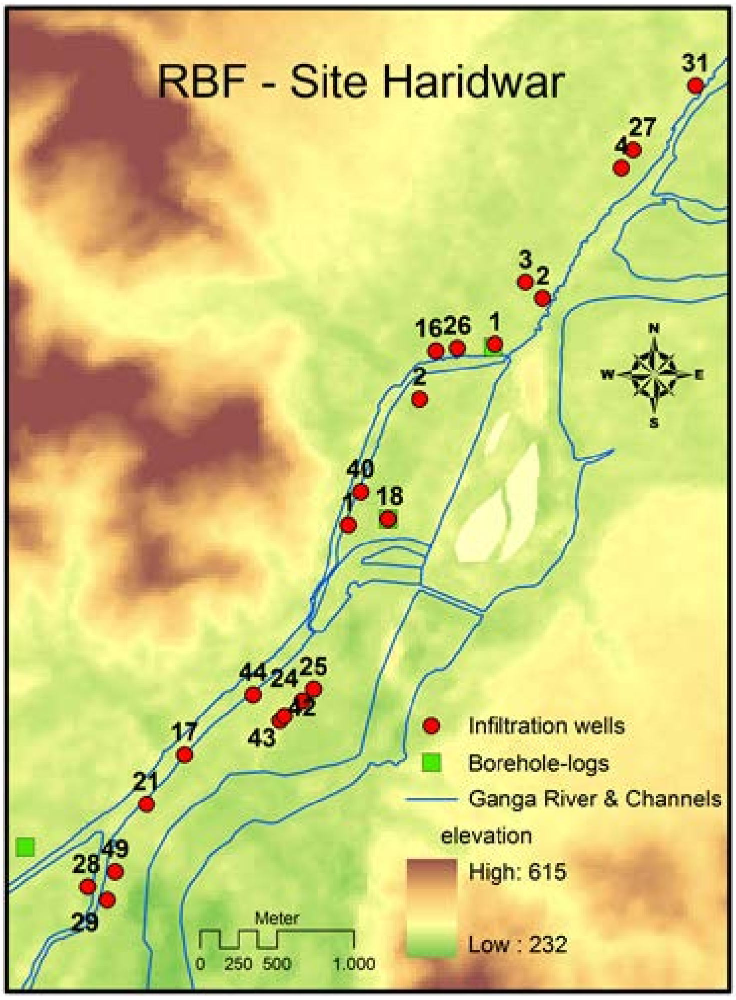

Figure 11 Infiltration wells of the RBF-Site in Haridwar

Most of the groundwater measurements are taken directly from the caisson (RBF) wells. The bottom-entry caisson wells are 6 – 10 m deep and are located 15 – 110 m from the Ganga river or the Upper Ganga Canal. As of April 2011, at least 12 wells operated continuously (24 hours), with the remaining wells operating for 9 – 19 hours per day. Each well usually has 2 – 3 fixed-speed vertical line shaft pumps, with each pump having a rated discharge of 600 – 2820 litres per minute (LPM), with a mean rated discharge of 1620 for all pumps. However, the pumps operate on a rotational basis for a fixed number of hours each day, which is necessary for the other pump(s) to cool and avoid malfunctions. Usually during the summer (pre-monsoon) and during religious festivals, the wells operate continuously as the demand for drinking water peaks. At other times only some wells operate continuously. The abstracted water is chlorinated at the wells and then supplied directly into the distribution network. The shortest travel time of bank filtrate to the RBF wells located on Pant Dweep island < 15 m from the bank of the surface water body is 2 days to > 100 days for wells located further away. These groundwater-levels are assumed to be the maximum drawdown. At some other infiltration wells, the groundwater is extracted for only a few hours, so that the measured groundwater-levels are not interpretable as a maximum drawdown. Therefore the groundwater-levels are validated by analysing their hydrographs. As shown in Figure 12, some of the groundwater-levels show an erratic behaviour which is due to the operation of the wells and time of measurement. Using the measured groundwater levels for the model calibration and for the estimation of initial conditions, they need to be analysed and corrected beforehand. Hence the correction is realised by drawdown and recovery curves which are derived for the relevant wells by pumping tests referring to Sandhu & Thakur (2006).

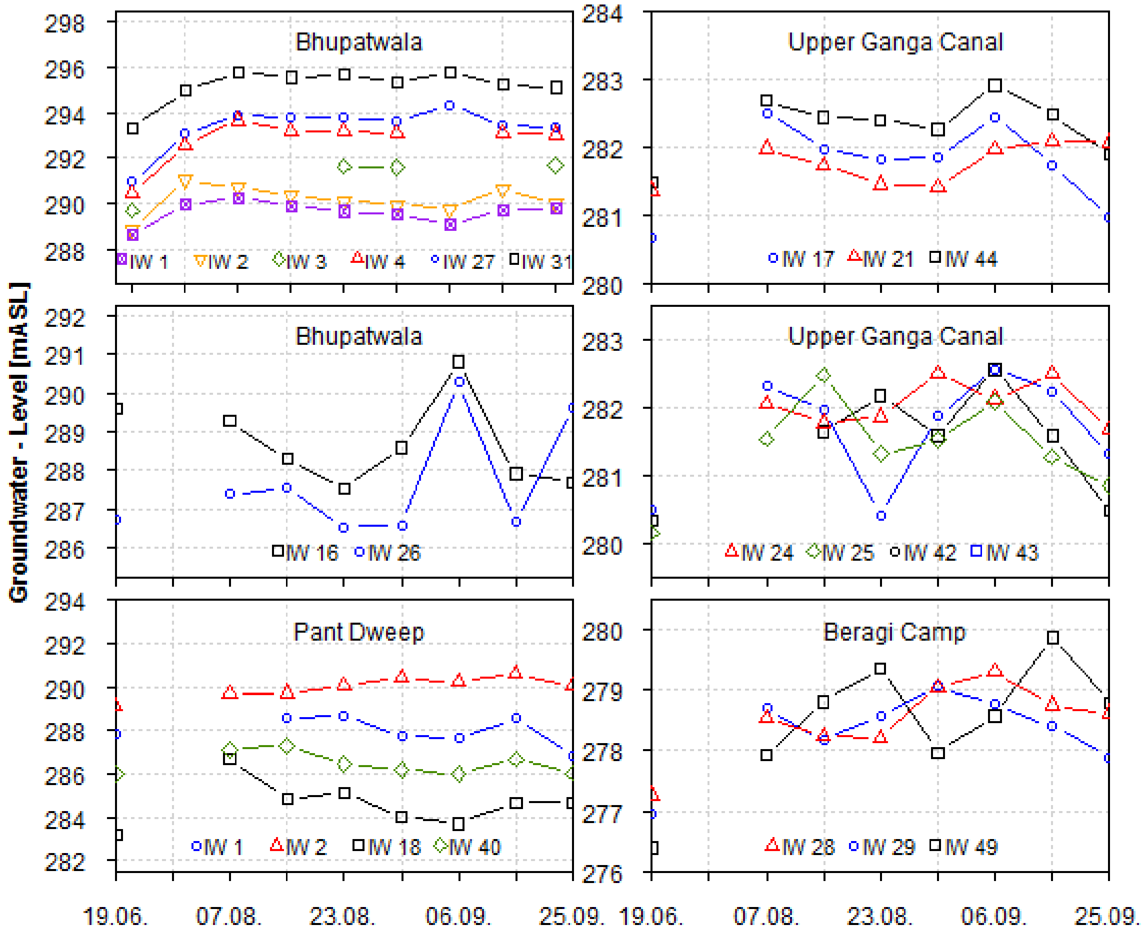

Figure 12 Groundwater-levels for each infiltration well (IW) at the RBF-Site Haridwar

3.4 Site-specific literature list

3.4.1 Publications (journals, conferences….)

CGWB (2009) Groundwater Brochure of Haridwar District, Uttarakhand. Government of India, Ministry of Water Resources, Central Ground Water Board (CGWB), Uttarakhand Region, Dehradun.

Census of India (2001) 2001 Census Results. Census of India, Office of the Registrar General, New Delhi.

Census of India (2011) 2011 Census Results. Census of India, Office of the Registrar General, New Delhi.

Dash RR, Bhanu Prakash EVP, Kumar P, Mehrotra I, Sandhu C and Grischek T (2010). River bank filtration in Haridwar, India: removal of turbidity, organics and bacteria. Hydrogeology Journal, 18(4), 973-983.

IS 10500 (1991) Indian standard (IS) specifications for drinking water. Bureau of Indian Standards, New Delhi, India.

Sandhu C, Schoenheinz D and Grischek T (2010) The impact of regulated river-flow on the travel-time and flow-path of bank filtrate in Haridwar, India. In: Zuber A., Kania J., Kmiecik E. (Eds.) Extended Abstracts, 38. IAH Congress, 12.-17.09.2010, Krakow, 2299-2305.

Sandhu C, Grischek T, Kumar P and Ray C (2011). Potential for riverbank filtration in India. Clean Technologies and Environmental Policy. 13(2), 295-316.

3.4.2 Other accessible data

All publications under Section D “Literature list” are publicly accessible

Healy RW and Cook PG (2002): Using groundwater levels to estimate recharge. Hydrogeology Journal. DOI 10.1007/s10040-001-0178-0.

Kumar CP (no date): Groundwater Assessment Methodology. National Institute of Hydrology, Uttarakhand India.

Sachse R (2005): Drinking Water Abstraction by River Bank Filtration (RBF). Report of Investigantion in Haridwar, India. University of Applied Sciences Dresden.

4 Srinagar RBF site

4.1 Synthetic site description

The town of Srinagar is located on the road to the important Hindu shrine of Badrinath in the Himalayas. The combined drinking water production for Srinagar and the town of Pauri (the water for which is abstracted and treated in Srinagar before being pumped 29 km to Pauri at an altitude of around 1660 m above MSL) in 2010 was around 3,750 m^3/day in contrast to a total demand of approximately 4,880 m^3/day (Kimothi et al. 2012). Currently around 80 – 82 % of the total raw water for the drinking water supply of Srinagar and Pauri is abstracted upstream of the town directly from the Alaknanda River. The abstracted surface water is passed through rapid sand filters and chlorinated before being supplied to the distribution network. However, similar to Haridwar, in the severe Monsoon of 2010 the surface water supply had to be discontinued due to excessive turbidity. Additionally the completion of a tunnel to divert a major portion of the flow for a river-run hydropower generation plant, the river will have a severely reduced flow along a 4 km stretch rendering current surface water abstraction system inoperable. Preliminary investigations show promising conditions for RBF in Srinagar (Figure 13; Sandhu et al. 2011). Although the flow of the Alaknanda River is sufficient throughout the year, over the period from the peak-monsoon (August–October) flows to the post-monsoon (January–February) flows the waterline can recede by as much as 190 m from the southern bank of river, especially in the area of the production well at Silk Farm. This would significantly influence the travel-time of bankfiltrate and result in changing redox conditions. On the other hand, extreme events like the monsoon of 2010 and 2011 resulted in the water-line of the river reaching within a few metres of the wells. Additionally, in land-side groundwater, high nitrate concentration was found, assumed to come from urban pollution with sewage.

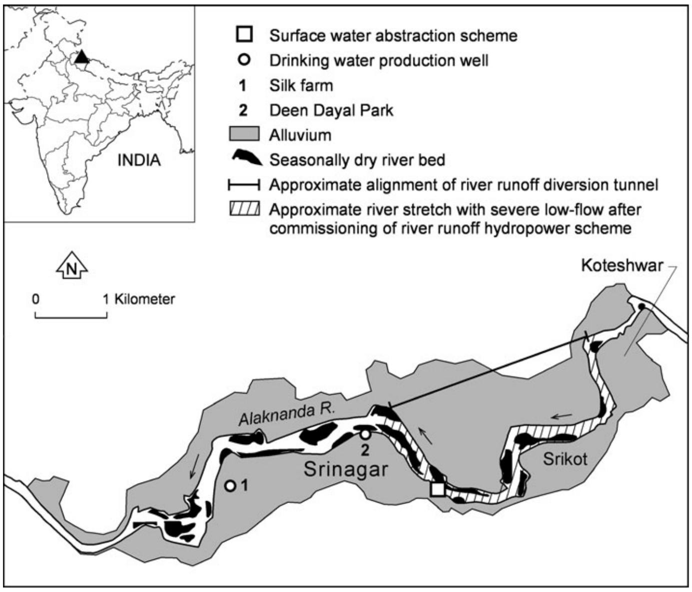

Figure 13 Srinagar, with the location of the new RBF site (1) (from Sandhu et al. 2011).

In May 2010, one production and one monitoring well (PW-DST & MW1) were constructed in the south-west part of the town (Figure 14) as part of a separate project (Kimothi et al. 2011). The wells were drilled up to a depth of 20 m BGL and at a distance of 170 m from the flood-protected riverbank. The interpretation of the borehole material showed that the aquifer comprises medium to coarse sand. Interpretation of pumping test data from PW-DST showed the hydraulic conductivity to be in the range of 7.7×10^{-5} – 4.0×10^{-3} m/s. The PW-DST currently operates for 20 – 22 hours/day with a production of 852 – 937 m^3/day. After abstraction and on-site disinfection by chlorination, the water is pumped into a storage reservoir and then supplied into the distribution network by gravity. The production from the PW-DST accounts for 18 – 22 % of the combined drinking water production of Srinagar and Pauri (Kimothi et al. 2012).

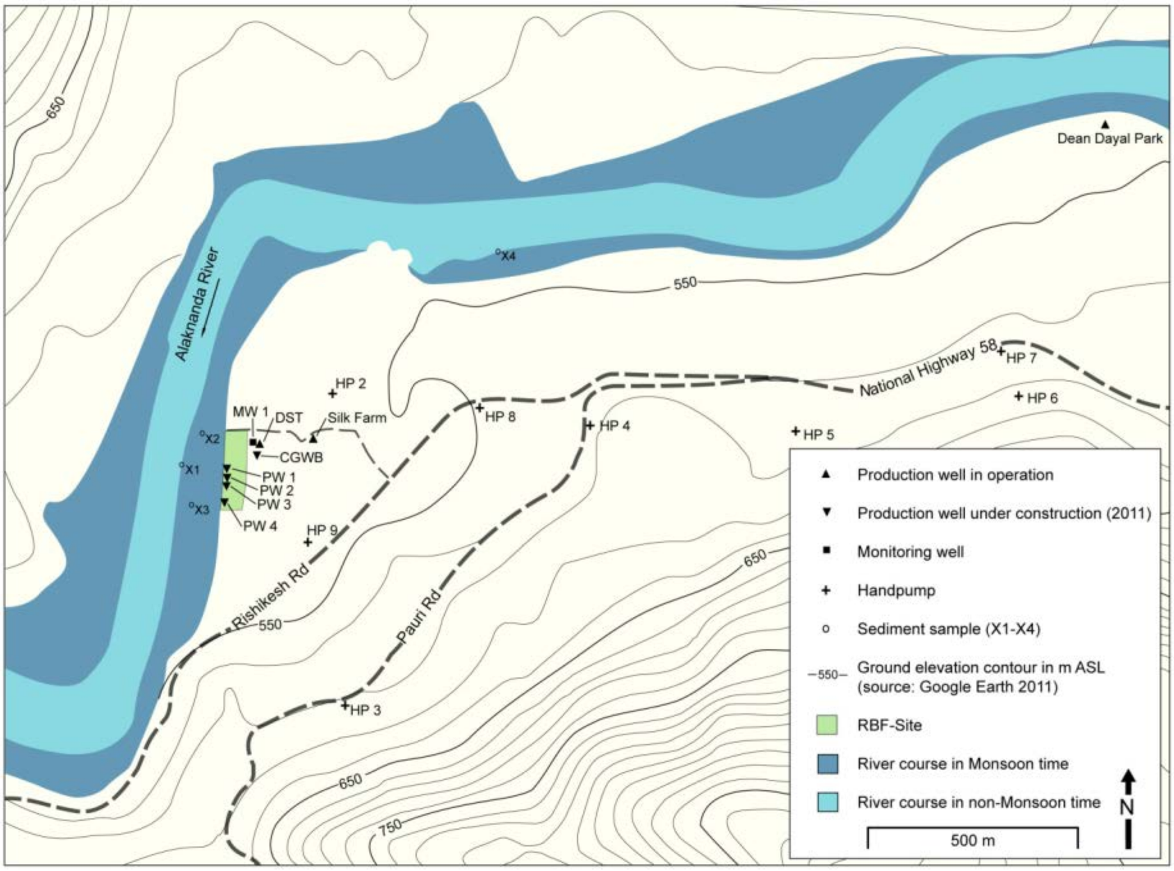

Figure 14 RBF well field in Srinagar under development since May 2010

In the period July – September 2011, four additional boreholes were drilled and casings, filter sections and filter gravel were installed in Srinagar in the area in between the wells drilled in 2010 and the river (Figure 14 and Figure 15, PW-DST & PW1…PW5). The PW-DST installed in 2010 revealed suitable hydrogeological conditions for RBF, although high nitrate concentrations (> 50 mg/L) in the abstracted water were observed after pumping commenced in 2010 with the abstraction of predominantly ambient groundwater. As potential exists in Srinagar to construct additional RBF wells near to the existing PW (2010), such a system of a battery of wells along the river will not only cater to future increases in demand, but will also increase the proportion of bank filtrate abstracted by the wells. An increased proportion of bank filtrate in the abstracted raw water is particularly useful in case of undesired high concentrations of nitrate in land-side groundwater. High nitrate concentrations in groundwater is a common occurrence in areas where agricultural activities lead to widespread fertiliser application or wastewater from leaky urban drains and sewers comes in contact with groundwater. Consequently, mixing of bank filtrate with ambient groundwater would lower the concentration in the water pumped by the well.

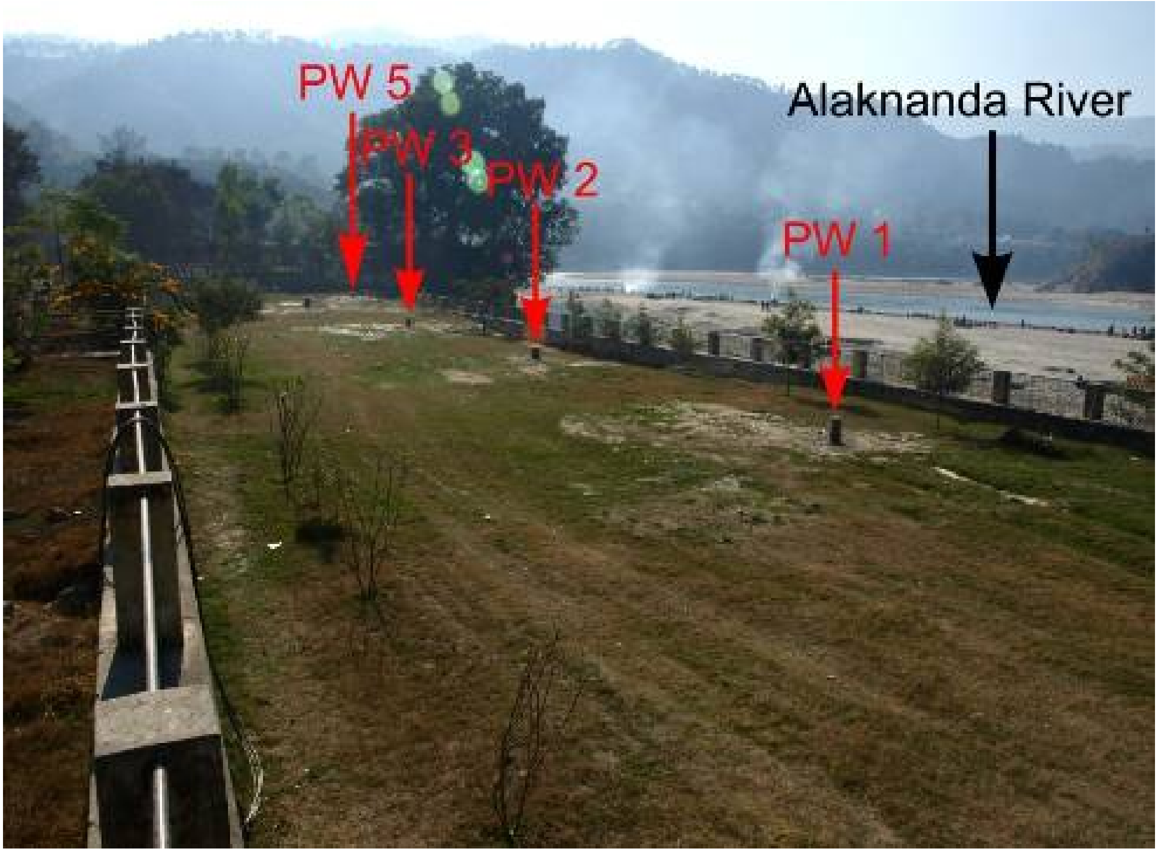

Figure 15 Four additional boreholes for production wells were drilled in July - September 2011 (Photo: F. Musche & E. Ballmann, HTWD, 2011)

Within the framework of the Saph Pani project, a monitoring well (MW4) was constructed in May 2012 by the project partners Akshay Jaldhara and Uttarakhand Jal Sansthan in between PW4 and the river (Figure 16). MW4 is 15.1 m deep and is situated at a distance of 4 m from the flood-protected river bank and 0.75 m from PW4. The close proximity to the high-flow mark of the river is intentional in order to investigate the removal efficiency of pathogens during monsoons and floods. The determination of the removal efficiency of pathogens, by comparing the total and fecal coliform counts of the abstracted water from PW4 and the Alaknanda, commenced in end September 2012.


a

b

Figure 16 (a) Monitoring well MW4 (left) constructed in Srinagar in between PW4 and the Alaknanda (Photo: K. Heinze, HTWD, May2012) (b) Pumping test and sampling being conducted on MW4 & PW4 (Photo: V.D.A. Nguyen, HTWD, September 2012)

4.2 Previous / Parallel project(s)

Project acronym/name: Development of Riverbank Filtration in Hill Regions for Sustainable Solution for Quality and Quantity Problems of Drinking Water in Uttarakhand

Duration: from 2010 – 2013

Framework: "Water Technology Initiative" of the Department of Science and Technology, Government of India (DST-WTI).

Coordination/partnership: Uttarakhand State Council for Science and Technology (UCOST). Partners: UJS and Cooperation Centre for Riverbank Filtration (CCRBF)comprising HTWD, IITR and water company Stadtwerke Düsseldorf AG

What was done: One production well (PW) and one monitoring well (MW) have been constructed at RBF sites in each of the four towns of Srinagar, Karnaprayag, Agastmuni and Satpuli. The PW in Srinagar and Satpuli are already abstracting water regularly and are connected to the drinking water supply network of these towns. As such, the development of RBF in hill-regions has commenced. Consequently the formulation of concepts for the quick selection of RBF sites is in progress.

Website or information on the web: no

4.3 Data collection and management

4.3.1 Data available at the onset of the project

No previous data available

4.3.2 Data requirements for modeling

Typical data requirements for PMWin

4.3.3 Status of data collection at M12

The following categories of data were measured and documented for the Srinagar site since October 2011:

a. Water levels: Regular groundwater (logger and manual measurements) and surface water level measurements have been documented in an excel file.
b. Distance of water-line of river to river bank has been documented for certain reference-day measurements
c. Water quality data consisting of physico-chemical parameters, major ions and pathogenic indicators have been documented into an excel file.
d. A subsurface cross-section has been constructed for the RBF site using borehole-logs available for the wells constructed at the RBF site
e. Hydraulic conductivities have been determined for the RBF site from pumping tests and for the riverbed material from grain-size distribution analyses.

A groundwater flow model was constructed using PMWIN (version 8.03) for the area covering around 2.4 km^2 shown in Figure 14.

The input parameters of the model are summarised in Table 9. The river in the model was assigned as constant head cells. The horizontal hydraulic conductivity of the riverbed was assigned to the model as a mean value of 4.5×10^{-2} m/s obtained after Beyer from sieve analyses of sediment taken from four different locations along the river, with a vertical hydraulic conductivity of 4.5×10^{-3} m/s. A horizontal hydraulic conductivity of 1.3×10^{-3} m/s obtained from pumping tests was assigned for the aquifer in the near-bank area along the entire river, with a vertical hydraulic conductivity estimated at 1.3×10^{-4} m/s. The effective porosity was set at 0.3. A recharge value of 3.96×10^{-8} m/s was assigned to the model based on a mean precipitation for the period 1965 – 1986 for the region of Srinagar. Due to the absence of site specific borehole data, the hill slope in the model above the relatively level RBF site was assigned a lower hydraulic conductivity of 6×10^{-6} m/s. Information obtained from a report of the construction of a dam a short distance upstream of Srinagar, indicates that a thin layer of topsoil covers a predominantly hard rock layer mostly in areas with a steep topography.

Table 9 Summary of groundwater flow model parameters for Srinagar RBF site

Model parameter	Assigned value
Geometry	Area: 1600 × 1500 m; 37 rows, 35 columns; cell size: 0.3 × 0.3 m to 100 × 100 m
Boundary conditions	River: assigned as constant head cells along western and northern boundary, interpolation of water levels measured on 10.12.2011
	Wells: total discharge of 0.06 m^3/s (5184 m^3/day) at 0.01 m^3/s per well for six production wells (PW-DST, PW-CGWB and PW1 to PW4)
	Recharge: 3.96×10^{-8} m/s assigned to uppermost active cells
Hydraulic conductivity	River cells: $K_x = K_y = 1 \times 10^{-3}$ m/s; $K_z = 1 \times 10^{-4}$ m/s
	Aquifer in flood plain area: $K_x = K_y = 3 \times 10^{-3}$ m/s; $K_z = 3 \times 10^{-4}$ m/s
	Hill-side slope: $K_x = K_y = 6 \times 10^{-6}$ m/s; $K_z = 6 \times 10^{-7}$ m/s
Effective porosity	0.3
Simulation	Steady state , unconfined conditions

4.4 Site-specific literature list

Kaur R, Kendall T (2008) Myth of power. Down To Earth, 17(8), 28–32.

Kimothi PC, Adlakha LK, Dobhal R, Ronghang M, Sandhu C, Grischek T, Kumar P, Mehrotra I, Voltz TJ, Rawat OP, Patwal PS (2011) Development of Riverbank Filtration in Hill Regions for Sustainable Solution for Quality and Quantity Problems of Drinking Water in Uttarakhand. Intermediate Project Report: March 2010 – December 2011, funded by “Water Technology Initiative” of the Department of Science and Technology, Government of India (DST-WTI).

Kimothi PC, Dimri DD, Adlakha LK, Kumar S, Rawat OP, Patwal PS, Grischek T, Sandhu C, Ebermann J, Ruppert M, Dobhal R, Ronghang M, Kumar P, Mehrotra I, Uniyal HP (2012) Development of Riverbank Filtration in Uttarakhand. *J. Indian Water Works Association*, July–September issue (*in press*).

Sandhu C, Grischek T, Kumar P and Ray C (2011). Potential for riverbank filtration in India. Clean Technologies and Environmental Policy. 13(2), 295-316.

5 Musi River site

5.1 Site specific background knowledge

5.1.1 Synthetic site description

The Musi River (Figure 17a) which flows through the city of Hyderabad is associated with an ancient irrigation system comprising a series of (natural/engineered) wetlands. The river receives over a 1.2 million m^3 /day of wastewater (both domestic and industrial) from the city which is only partially treated and used for irrigation, either directly via a system of irrigation canals or after storage in sedimentation tanks. The wastewater is a significant resource in this semi-arid periurban environment where the cultivation of fodder grass, paddy and vegetables has provided economic benefits to many inhabitants of the area. Year round cultivation, which generates large return flows from irrigated fields, contributes to a large share of the aquifer recharge. Shallow groundwater is also pumped locally for irrigation on terrains where canal water is not accessible, or where it is too polluted for certain crops, especially paddy rice (Amerasinghe et al., 2008). The Musi river flow is broken by a series of weirs, creating small small reservoirs, from where water is diverted into irrigation canals and village tanks to be used by farmers for crop production (Ensink et al. 2009).

Saph Pani studies will be carried out in the “Kachwani Singaram” catchement (wetland), which is situated in the left bank of the Musi River (Figure 17b), and is around 10 km away from the city of Hyderabad (Schmitt, 2010, Perrin et. al, 2011). It is one of the rice growing regions close to the city and constitues around 2.74 km^2, dominated by wastewater irrigation. Other crops are paragrass and vegetables.

Hydrogeologcial conditions: composed of orthogneissic granite as basement with granite, quartz and dolerite intrusions. For details see reports of Schmitt (2010), Perrin et al. (2011) and Aellen, (2011).

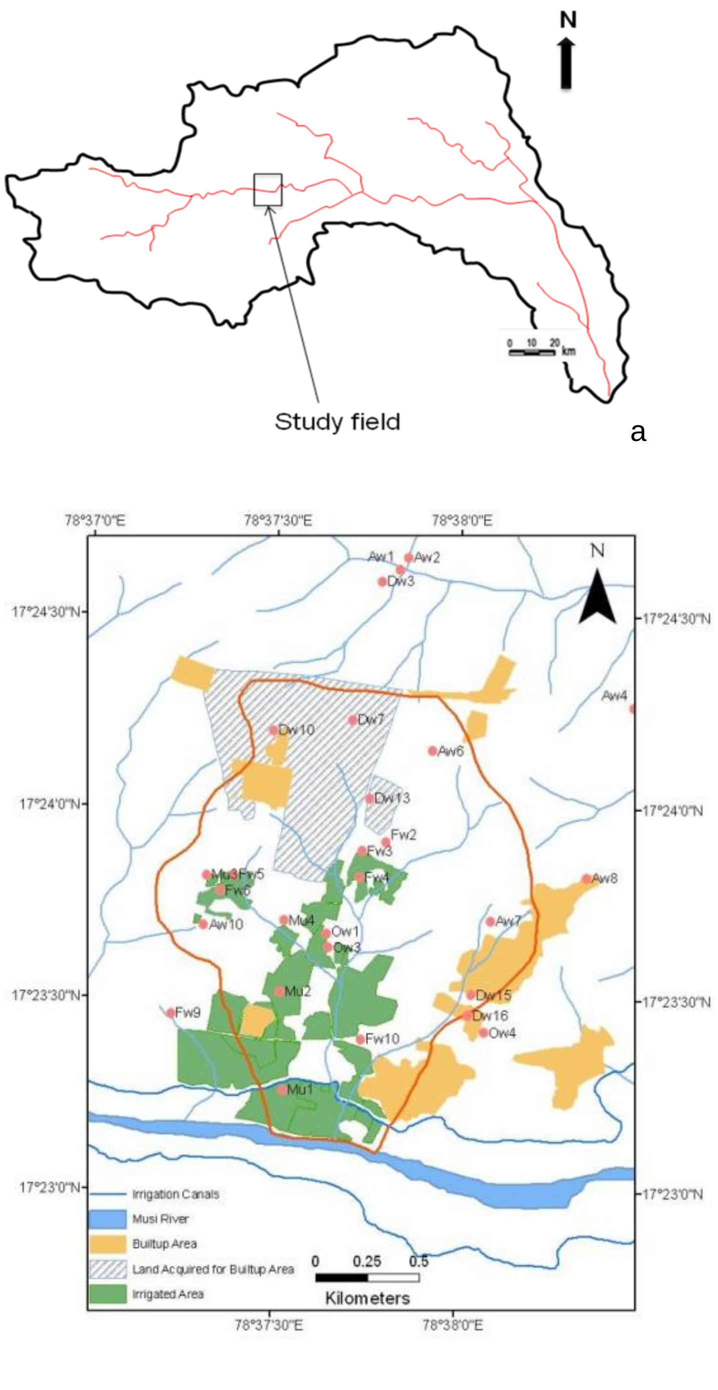

Figure 17 (a) Situation of the Kachwani Singaram Micro-Watershed in the Musi River basin, (b) Spatial Distribution and Land use map

5.1.2 Previous projects

Project acronym/name: Assessing groundwater processes in a periurban micro-watershed in Hyderabad.

Duration: 2009/2010

Framework: IWMI funding

Coordination/partnership : IWMI, BRGM, NGRI (IFCGR)

What was done: An area (280 ha) comprising wastewater- and groundwater-irrigated agriculture was selected for detailed study based on land-use maps and observations. The watershed was delineated using DEM and GIS data. A crop model (BUDGET; Raes, 2005) was combined with field measurements, baseline data on irrigation practices, and land use patterns, to assess the overall water balance. The suitability of the method was validated with questionnaire survey results and available secondary data. Four piezometers were installed to assess and monitor groundwater levels and quality. Base-line data for 23 distinct fields were collected.

Master Thesis: Schmitt, 2010 "Wastewater reuse in Indian peri-urban agriculture Assessment of irrigation practices in a small, peri-urban catchment in Hyderabad, Andhra Pradesh, India"

Website or information on the web: none

Project acronym/name*:* Assessing groundwater processes in a periurban micro-watershed in Hyderabad.

Duration: 2009/2010

Framework: IWMI funding

Coordination/partnership: IWMI, BRGM, NGRI (IFCGR)

What was done: This study defined the impact of different types of irrigation water (surface water, mix water between canal water and groundwater, and groundwater) on groundwater quality, determine the interaction between Musi river and groundwater, characterized the aquifer properties (piezometric map, transmissivity, conductivity, groundwater budgeting) in the representative hydrogeological unit of Kachwani Singaram and evaluated the impact of scenarios of future water uses on the groundwater system.

Project Report: Perrin et al. 2011 "Groundwater processes in a micro-watershed influenced by wastewater irrigation, peri-urban Hyderabad."

Website or information on the web : none

Project acronym/name*:* Assessing groundwater processes in a periurban micro-watershed in Hyderabad.

Duration: 2009/2010

Framework: IWMI funding

Coordination/partnership: BRGM, NGRI (IFCGR), IWMI

Master Thesis: Aellen, 2011.

What was done: The interpretation of piezometric maps allowed to distinguish two hydrodynamic phases of the water; The first phase, during the monsoon, with a north-south flow. During this phase the influence of the pumping wells is not significant. On the contrary the reduction of the water with the arrival of the dry season, shows a stronger influence on the wells. This is also noticeable by the reversal of the local hydraulic gradient inducing a change of the direction of groundwater flow.

The water balance calculations showed the significance of irrigation in the process of groundwater recharge. This dynamic can worsen the quality of the upstream water. A numerical model based on those information was developed in order to help to the overall understanding of the watershed and to help to conceptualize several scenarios.

Website or information on the web:

Project acronym/name*:* Water Quality, Health and Agronomic Risks and Benefits Associated with "Wastewater" Irrigated Agriculture

Duration: 2005 - 2007

Framework: BMZ funding

Coordination/partnership: IWMI, Freiburg University, Applied Geography of the Tropics and Sub-tropics (APT), Freiburg. International Livestock Research Institute (ILRI), Hyderabad

Centre for Economic and Social Studies (CESS), Hyderabad and Environment Protection Training and Research Institute (EPTRI), Hyderabad

What was done: Framework of actors and interactions. Social and institutional map of the multiple actors (individuals and organizations) along the chain from wastewater source to end-use. GIS database of urban and periurban agriculture and wastewater irrigation. Evaluation of human health and agronomic risks from field to consumer. Economic valuation of the direct and indirect livelihood benefits as well as the health and adaptation-related costs of wastewater irrigation. Comprehensive assessment of tradeoffs, risks, costs and benefits at different levels along the chain from wastewater users to consumers of produce. Concrete, actionable risk mitigation recommendations (based on outputs 1-5 above).

Website or information on the web: Amerasinghe et al. 2008

5.2 Data collection and management

5.2.1 Data available at the onset of the project

The geology, hydrogeology and hydraulic parameters are available in Schmitt, 2010, Perrin et al. 2010, Aellen, 2011. Available data are given in an Excel spread sheet.

5.2.2 Status of data collection at M12

The Kachwani Singaram catchement-wetland has has been targeted as study area within the Musi watershed partly due to its good background data situation obtained in former projects (IWMI, BRGM, NGRI (IFCGR). IWMI developed a monitoring plan for activities in the Musi river site. The time schedule has also been planned, and preliminary characterization (surface water flows, crops grown etc.) has commenced. Monitoring of water levels has started (Table 10) and the schedule foresees a complete measurement program for May-June.

Table 10 : Monitoring programme for Musi study site (Kachwani Singaram catchement) for 2012

	2012								rainy season						
	Description of measurement	**Frequency**	**Period of Monitoring**												**Participating Institutions**
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Surface water	Discharge measurements	Monthly	-	-	-										ÌWMI
	Water quality	Pre & post monsoon	-	-	-	-			-	-	-			-	NGRI/BRGM/IWMI
Groundwater	Water level monitoring and discharge measurements	Monthly													NGRI/BRGM
	Water quality	Pre & post monsoon	-	-	-	-			-	-	-			-	BRGM/NGRI/IWMI
Soil	Soil quality	Pre & post monsoon	-	-	-	-			-	-	-			-	IWMI
	Soil textural analysis	Pre & post monsoon	-	-	-	-			-	-	-			-	IWMI
Plant/Biomass	Quality	Pre & post monsoon	-	-	-	-			-	-	-			-	IWMI
Geo-physical studies		-	-	-	-	-			-	-	-			-	NGRI

Based on the monitoring plan, the pre-monsoon sampling of water, soil and plants was carried out by IWMI and NGRI in June, 2012. Physical, chemical (organic and Inorganic elements – anions, cations, nutrients, heavy metals and pesticides), microbiological and helminth analysis were performed. Physical, chemical and microbiological analysis for water, soil and plant samples were carried out at NGRI and NCMSL laboratory, in Hyderabad and helminth analysis was carried out at IWMI.

Water level measurements in the bore wells/piezometers, discharge measurements and in-situ water quality measurements were carried out by IWMI and NGRI. For detailed studies, a paddy field ecosystem was identified and the experimental design for monitoring the wetland functions was established. The instruments required for assessments have been ordered, however, there have been delays, due to the unavailability of stocks in India.

5.3 Site-specific literature list

5.3.1 Publications (journals, conferences….)

Amerasinghe, A., P. Weckenbrock, R. Simmons, S. Acharya, and M. Blummel (2008). An atlas of water quality, health and agronomic risks and benefits associated with “wastewater” irrigated agriculture an atlas of water quality and agronomic risk and benefits associated with "wastewater" irrigated agriculture. a study from the banks of the musi river, india. Published online: http://www.freidok.unifreiburg.de/volltexte/6963/

Ensink, J. H. J., C. A. Scott, S. Brooker, and S. Cairncross (2009). Sewage disposal in the musi-river, india: water quality remediation through irrigation infrastructure. Irrigation and Drainage Systems.

Massuel, S., Biju George, Anju Gaur, Rajesh Nune. (2007). Groundwater Modeling for Sustainable Resource Management in the Musi Catchment, India. MODSIM07 Conference Proceedings. p. 1429-1435 http://www.mssanz.org.au/MODSIM07/papers/23_s31/Groundwater_s31_Massuel_.pdf

McCartney M., Scott C., Ensink J., Jiang B. and Biggs T. W., (2008). Salinity implications of wastewater irrigation in the Musi River catchment in India. Cey. J. Sci. (Bio. Sci.) 37 (1): 49-59

J. Perrin, S. Ahmed, L. Dinis, V. Aellen, P. Amerasinghe, P. Pavelic, R. Schmitt (2011). Groundwater processes in a micro-watershed influenced by wastewater irrigation, peri-urban Hyderabad. Hyderabad, National Geophysical Research Institute (NGRI), Bureau de recherches géologiques et minières (BRGM), International Water Management Institute (IWMI). IFCGR/IWMI 2009 – 2010. Pp 54

Schmitt, R. (2010). Wastewater reuse in Indian peri-urban agriculture Assessment of irrigation practices in a small, peri-urban catchment in Hyderabad, Andhra Pradesh, India: Mémoire, Swiss Federal Institute of Technology. Pp 93

Biggs, T. W., and B. Jiang. (2009). Soil Salinity and Exchangeable Cations in a Wastewater Irrigated Area, India. J Environ Qual 38 (3):887-896.

Van Rooijen D.J., H. Turral, T.W. Biggs, (2005), Sponge city: Water balance of mega-city water use and wastewater use in Hyderabad, India, Irrigation and drainage, 54, S81-S91.

Aellen, V. (2011). Etude Hydrogeologique Et Modelisation D’un Bassin Versant En Inde Master En Hydrogéologie Et Géothermie Spécialisation En Hydrogeology Centre D’hydrogéologie Et Géothermie Université De Neuchâte. Pp 77

6 Maheshwaram site

6.1 Site specific background knowledge

6.1.1 Synthetic site description

One of the main experimental watersheds relevant for MAR studies in WP2 is located around the town of Maheshwaram (Figure 18). With a total area of 54 km^2, it is located in a semi-arid hard-rock context typical for the entire region where the saprolite layer (10-20 m thick) is usually unsaturated. It is a watershed with a high density of groundwater production wells (>700) mostly for paddy irrigation; changes in land use have occurred since 2006, the new Hyderabad international airport being located less than 10 km away. It is expected to become a peri-urban area within the coming years as significant housing projects are planned. MAR has been implemented throughout the watershed in the form of percolation tanks, check dams, defunct dugwells, etc. over the last decade.

Intensive groundwater exploitation for irrigation has resulted in aquifer over-exploitation and deterioration of groundwater quality (fluoride above maximum permissible limit of 1.5 mg/L, salinisation and agricultural inputs). MAR is an attractive concept for groundwater augmentation and enhanced groundwater quality nearby wells exploited for domestic uses. The objective of the tasks in WP2 for the case study site in Maheshwaram is to investigate the potential of percolation tanks and defunct dug wells to enhance recharge and groundwater quality in the underlying overexploited hard-rock aquifer by implementing a sophisticated monitoring strategy for groundwater levels and quality, conducting hydrogeochemical analyses and investigating the hydrodynamics with the support of a conceptual groundwater balance model developed in cooperation with WP5.

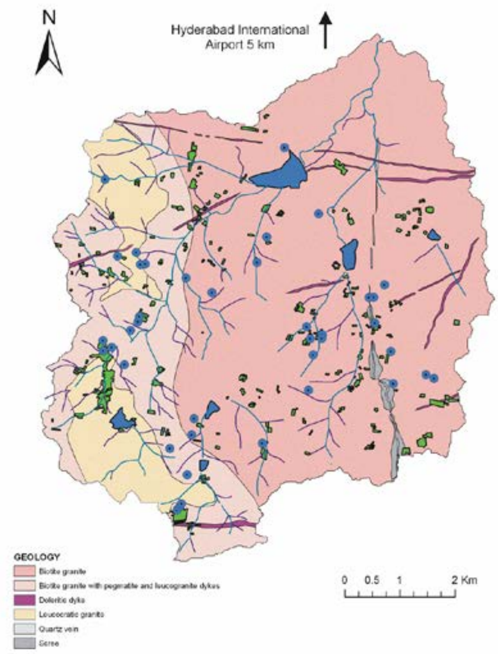

Figure 18 Geological map of Maheshwaram watershed. Main MAR (percolation tanks and defunct dugwells) structures are indicated in blue Green areas are irrigated paddy fields.

6.1.2 Previous projects

Project acronym/name: MOHINI Project: Integrated MOdelling of Hard rock aquifers : Vulnerability to global change of anthropogenic origin

Duration: from 2008 to 2011

Framework: ANR funding

Coordination/partnership: BRGM / NGRI, Géosciences Rennes, Géosciences Montpellier, ITASCA, Strasbourg

What was done: At Maheshwaram, groundwater is the main source of drinking water supply and is characterized by a high variability of fluoride concentrations often exceeding the drinking water limit. During the course of the MOHINI project, whereas fluorosis has never been detected before, a study of the effectiveness of dental fluorosis prevalence in the school age (6-18 years old) population of Maheshwaram has revealed that 89 % of the 501 children surveyed exhibited various degree of dental fluorosis, with about 6 % presenting a severe dental fluorosis. At the same time, geochemical investigations allowed a better understanding of the processes responsible for fluoride accumulation. These investigations led to a geochemical model tested for various conditions corresponding to 3 evolution scenarios by the year 2014 in agreement with the 2020 vision of Andhra Pradesh government.

Project acronym/name: QUANTIFICATION OF HYDROLOGICAL FLUXES IN IRRIGATED LANDS USING ISOTOPES FOR IMPORVED WATER USE EFFICIENCY

Duration: from 2009 to 2011

Framework: AIEA Funding

Coordination/partnership: BRGM/NGRI

What was done: Paddy field hydrodynamics was investigated by combining different methods: water fluxes direct monitoring, sampling of conservative tracers (chloride, stable isotopes) during one hydrological year, a conservative tracer (Br) test. The results bring a refined conceptual model of irrigation return flows and a quantification of the water fluxes at paddy field scale : infiltration, evaporation, transpiration.

Website or information on the web:

Project acronym/name**:** Setting-up the Maheshwaram experimental watershed

Duration: since 2000

Framework: BRGM, NGRI

Coordination/partnership: APGWD, BRGM, NGRI

What was done: Over twenty piezometers were drilled for a monthly piezometric monitoring and geological description. Geological mapping was carried out supported by geophysical measurements (VES, resistivity logging, etc.) and maps of weathering profile thicknesses were performed. Hydraulic tests (slug tests, flowmeter, aquifer tests) were performed both on the regular weathered granite (Maréchal et al. 2004) and on quartz reefs (Dewandel et al. 2011) for determination of aquifer hydrodynamic properties.

A meteorological station was set up in 2000 for rainfall, evaporation, wind speed and temperature measurements. Since 2001, seasonal piezometric campaigns have been carried out on over 100 piezometers and abandoned irrigation wells. A well inventory was carried out in 2002. These data were used to compute the groundwater balance at watershed scale. An irregular number of piezometers were equipped with automatic water level recorders. Groundwater chemistry monitoring (major ions, some traces, stable isotopes) is carried out since 2006 on over 30 wells. A preliminary study on artificial recharge using a dug well was carried out in 2005-2006 at the “recharge site” with implementation of piezometers, derivation of runoff to a defunct dug well, and water level monitoring in the dug well.

Website or information on the web : www.ifcgr.net

6.2 Data collection and management

6.2.1 Data available at the onset of the project

Geology

- Various drilling reports and observations
- Geological map
- Weathering thickness maps

Hydrology

- No data – no permanent streams

Hydrogeology

- Water levels: 2 wells IFP9 & IFP5 monitored from 2002 to 2012 (15 minutes time step); more piezometers monitored previously
- Piezometric campaigns: twice a year from 2001 to 2012 (~100 wells)
- Piezometric monthly data in 25 selected wells (2000 to 2008)
- infiltration, pumping tests on IFP wells (~25)
- Well inventory with discharge measurements (2002)

Meteorology

- Monthly rainfall 1984 to 2012
- Instant rainfall: (2000 to 2008)
- Temperature, wind velocity, evaporation: (2000 to 2008)

Landuse

- Two interpreted satellite imagery (2003, 2008)

Soil structure

- De Condappa et al. (2008)

Chemical data:

- Sampling campaigns at watershed scale:
  a) 2006 – 4 Campaigns (January, March, June, November)- 22 boreholes – Anions, Cations, traces
  b) 2008 – 1 Campaigns (June)- 10 boreholes – Anions, Cations,
  c) 2009 – 2 Campaigns (February, September)- 10 boreholes – Anions, Cations, traces
  d) 2011 – 1 Campaigns (June,)- 10 boreholes – Anions, Cations, traces
- GW dating: 2 Campaigns – June 2008, February 2009 – CFC, SF6
- Specific location: Experimental paddy field:03/02/09 to 19/03/10 – anions, cations, traces

- Rainwater: Since 2008 (?) anions cations traces, Isotopes (O18, D)

Access to the data: Most of the cited data are available from IFCGR.

Part of the data included in access database

Part of present in GIS form

6.2.2 Data requirements for modeling

Table 11 Data requirements for hydrogeological modelling at Maheshwaram site

Hydrogeological needs	Parameters	Acquisition Lab/field
Hydrogeological properties of soil	- hydraulic conductivity - Porosity	Tracer tests / infiltration test
	Retention capacity	Retention curves / infiltration tests
Hydraulic conditions	Precipitation	Meteorological Station
	Flow (Drainage)	Lysimeter
	Hydraulic Head (piezometric level)	Piezometers
	Evapotranspiration	Meteorological Station
	- Suction - Soil humidity	- Tensiometer - TDR
Topographic data		

Table 12 Data requirements for geochemical modelling at Maheshwaram site

Geochemical needs		Measures	Acquisition Lab/ in situ
Parameters needed (initial state, before infiltration & monitoring)	Recharge Water	Chemical composition*, pH, Eh, T°C, TDS, conductivity, Pathogens**	Sampling
	Soil Water	Composition*, pH, Eh, T°C TDS, conductivity	Porous Cups
	Rain Water	Composition*, pH, Eh, T°C, TDS, conductivity	Sampling
	Soil composition	Mineralogy (quantitative/qualitative) , CEC	XRD, X-fluorescence
Database	Gas-water-rock interaction + Bacteria	Kinetic reactions DOC (type), pH, Eh T°C, + redox species speciation	Batch/laboratory experiments/bibliography Mircroorganisms potential activity

*Composition = Na, Mg, K, Ca, F, Ctot, NO_2/NO_3, SO_4, PO_4, HCO_3, Br, DOC, TOC, Si, Li, Al, Mn, Co, Ni, Cu, Zn, As, Mo, Pb, U, B, Ba, Sr, Fe_{tot}, FeII/FeIII

**Pathogens: sulfate-reducing, Escherichia coli, Enterococcus, RNA specific bacteriophage, Enteroviruses, Cryptosporidium Oocytes, Giardia cysts.

- System behavior (modelling from monitoring, experimental data): detailed approach
- Hydrogeological model
- Geological profile, suction, moisture content, climatic parameters, hydraulic head, tracer test, pumping test
- Reactive geochemical model
- Water analysis: define recharge infiltration solution with chemical analysis of the measured infiltrating water composition
- Rock analyses: identify specific soil mineralogy using chemical and mineralogical (X-Ray diffraction), analyses of the experimental soil (detailed CEC analysis (shale and hydroxides), granulometry, effective porosity, permeability…) and potential

mineralogical secondary phases from infiltration solution interacting with soil (batch experiments to be performed to know equilibrium state of the system)

6.2.3 Status of data collection at M12

Data available at the watershed scale are given in the section 6.2.1 of this report. Within the Saph Pani project a special focus is laid on the detailed monitoring of a percolation tank. To meet the requirements for the modelling given in Table 11 and Table 12, the following actions have been taken to monitor the percolation tank located close to Tummulur village.

Six new boreholes have been drilled close to and within the tank. Localisation of the boreholes is given in Figure 19.

Drilling cuttings were analysed to provide the needed information on the geology of the area. Geophysical measurements have been carried out. Electrical resistivity profiles and borehole logging by dipole resistivity has been performed and a good correlation with drilling speed provides reliable information on the structure of the weathering profile of the zone. This geological conceptual model will be completed by borehole temperature and conductivity logging to provide more information on the localisation of productive fractures and their relative yields.

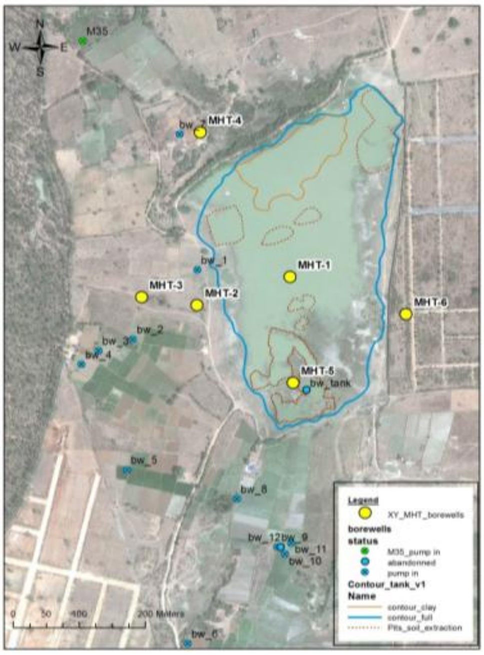

Figure 19: Maheshwaram borewells localisation

Hydraulic conditions are investigated by regular piezometric monitoring. All boreholes will soon be equipped with automatic water level recorders including temperature and conductivity measurements. Recent results provided in Figure 20 show an increase of the water levels. Those water levels are actually 1-3 m below the ground level in the tank (MHT 1, MHT5 and MHT7).

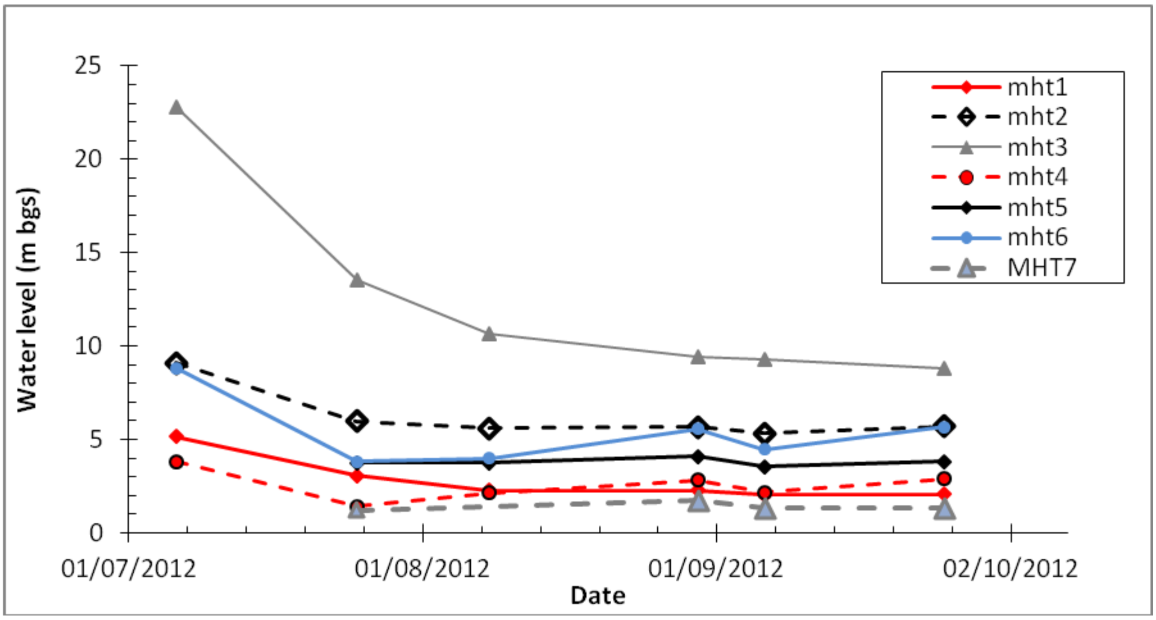

Figure 20: Water levels evolution in the piezometers

Precipitation is continuously monitored using the instant rainfall meteorological station. Cumulative rainfall is 671 mm on September 22th 2012. Rainfall repartition is given in Figure 21.

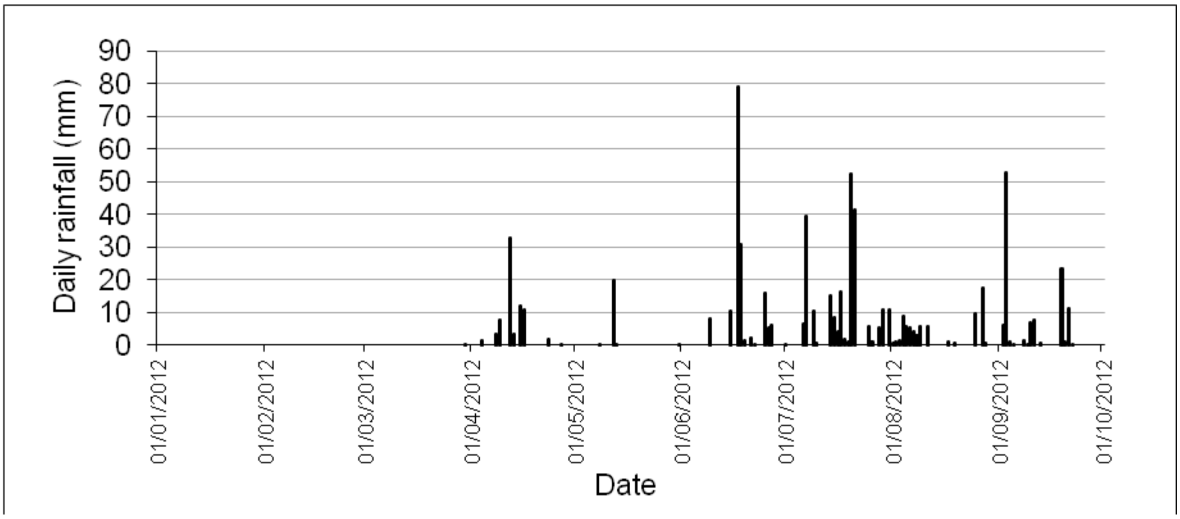

Figure 21: Daily rainfall at Maheshwaram meteorological station

The flooded part of the tank is monitored using automatic water level recorder and using direct observation on a scale. A second water level recorder is also attached to the scale and allows recording conductivity. This sensor is not accessible due to high water level. It will be removed at the end of the rainy season. A view of the tank on September 6th 2012 is provided Figure 22 and water level evolution in the tank is given Figure 23. Those data shows that the tank is filled only during and after the extreme rain events with sharp increases.

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Figure 22: View of the tank on September 6th 2012

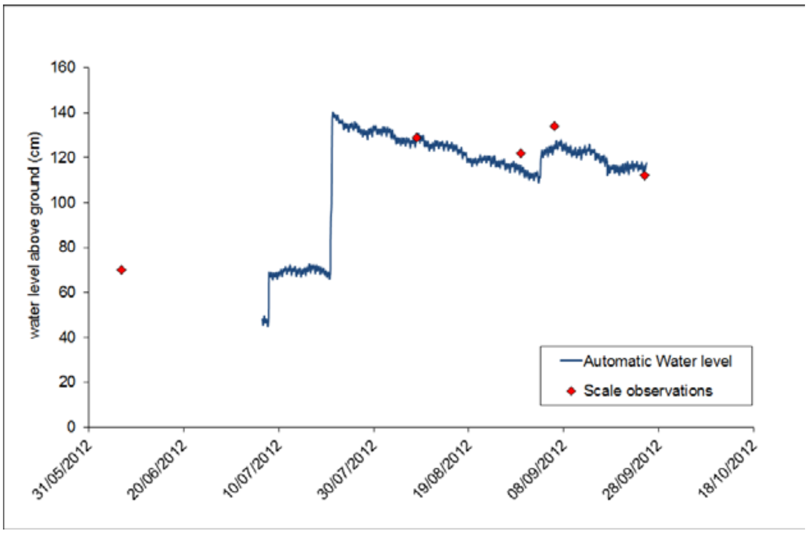

Figure 23: Water level evolution in the tank

GPS tracking around the tank is regularly performed. Coupled with the bathymetry survey previously realised, it allows the monitoring of the tank volume evolution.

Soil properties have also been investigated by auger drilling, infiltration tests and permeability measurements on samples.

All data available on the site are summarized in the following Table 13:

Table 13: Data available from the percolation tank monitoring

Data type	Parameters	Data status
Continuous monitoring	Piezometric level	6 boreholes water level measured since 06/07/2012
	Tank water level	Continuous monitoring since 06/07/2012
	GPS Trackings	5 trackings since 01/05/2012
	Rainfall	Continious monitoring since 01/01/2012
Specific Measurements	Geophysics	ERT profiles

		DRL Loggings
	Drilling cuttings analysis	MHT1 to MHT6
	Topography measurements	Complete tank
	Permeability measurements	5 points
	Infiltration tests	5 points
	Slug test	1 borehole

The following reports are available:

Table 14: Produced reports on the Tummulur percolation tank

Produced reports	Institution	Date
Drilling report in Maheshwaram Percolation tank	BRGM	2012 July
Implementation of Maheshwaram percolation tank monitoring network	BRGM	2012 August
Technical report: soil hydraulic properties in percolation tank...NGRI-2012-GW-802	NGRI	2012 May

6.2.4 Data management

All existing data are available in raw format or excel files for the continuous monitoring data. Relevant data are included in a GIS database. GIS available data are summarized in the Table 15 and examples of maps are presented Figure 24.

Table 15: GIS Data available on the Tummulur tank

GIS Data available
Satellite view of the watershed
Satellite view of the tank
Borewells localization including farmers borewells
Area topography
ERT profiles localization
Tank contouring including pit localization and GPS trackings of the flooded area

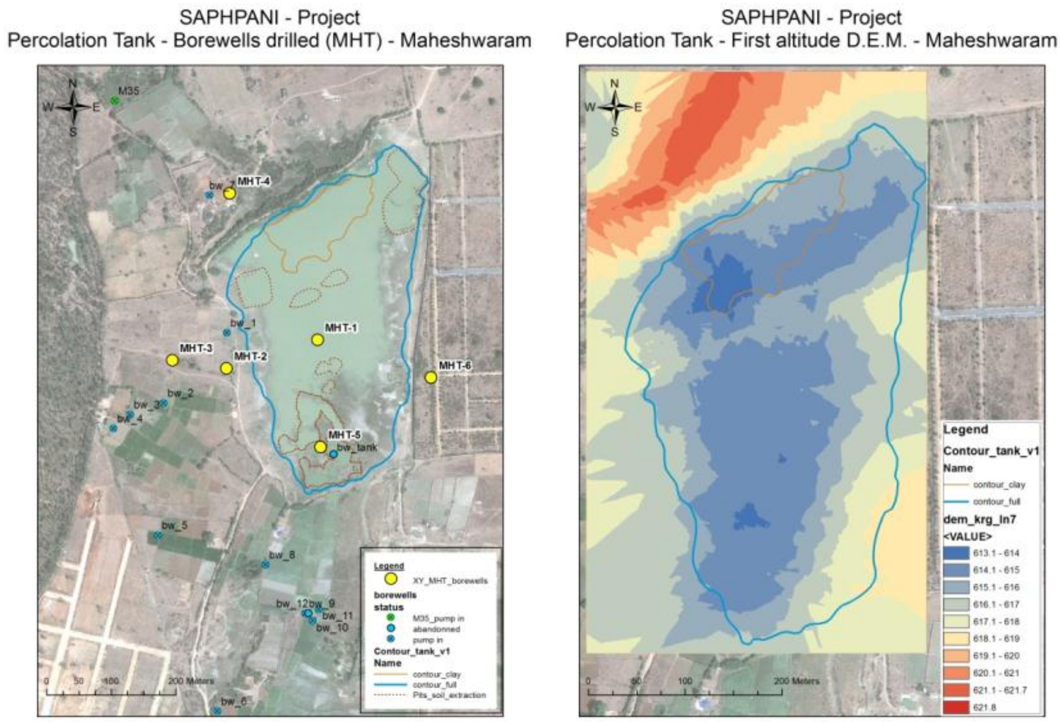

Figure 24: Tummulur tank mapping: a) Borewells localization including farmers borewells and tank contouring; b) Topography of the area

6.3 Site-specific literature list

6.3.1 Publications (journals, conferences….)

Chandra, S., S. Ahmed, et al. (2008). "Estimation of hard rock aquifers hydraulic conductivity from geoelectrical measurements: A theoretical development with field application." Journal of Hydrology 357(3-4): 218-227.

de Condappa, D., S. Galle, et al. (2008). "Bimodal zone of the soil textural triangle: Common in tropical and subtropical regions." Soil Science Society of America Journal 72(1): 33-40.

Dewandel B., J.C. Maréchal, O. Bour, B. Ladouche, S. Ahmed, S. Chandra, H. Pauwels (2012) “Upscaling and regionalizing hydraulic conductivity and effective porosity at watershed scale in deeply weathered crystalline aquifers.” Journal of Hydrology, (416–417): 83–97.

Dewandel, B., P. Lachassagne, F.K. Zaidi, S. Chandra (2011) ”A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers: example of a quartz reef in granitic terrain in South India” Journal of Hydrology 405): 474–487.

Dewandel, B., J. Perrin, S. Ahmed, S. Aulong, Z. Hrkal, P. Lachassagne, M. Samad, S. Massuel (2010) “Development of a tool for managing groundwater resources in semi-arid hard rock regions. Application to a rural watershed in south India" Hydrol. Process., (24): 2784–2797.

Dewandel, B., J.M. Gandolfi, D. de Condappa, S. Ahmed (2008) "An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scales" Hydrol. Process., (22):1700–1712.

Dewandel, B., J.-M. Gandolfi, et al. (2007). "A decision support tool with variable agroclimatic scenarios for sustainable groundwater management in semi-arid hard-rock areas." Current Science 92(8): 1093-1102.

Dewandel, B., P. Lachassagne, et al. (2006). "A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering." Journal of Hydrology 330(1-2): 260-284.

Dutta, S., N. S. Krishnamurthy, et al. (2006). "Localization of water bearing fractured zones in a hard rock area using integrated geophysical techniques in Andhra Pradesh, India." Hydrogeology Journal 14(5): 760-766.

Khan, H. H., A. Khan, et al. (2011). "GIS-based impact assessment of land-use changes on groundwater quality: study from a rapidly urbanizing region of South India." Environmental Earth Sciences 63(6): 1289-1302.

Khan, H. H., A. Khan, et al. (2011). "GIS-based impact assessment of land-use changes on groundwater quality: study from a rapidly urbanizing region of South India." Environmental Earth Sciences 63(6): 1289-1302.

Krishnamurthy, N. S., D. Kumar, et al. (2003). "Comparison of surface and sub-surface geophysical investigations in delineating fracture zones." Current Science 84(9): 1242-1246.

Marechal, J. C., R. Wyns, et al. (2004). "Vertical anisotropy of hydraulic conductivity in the fissured layer of hard-rock aquifers due to the geological patterns of weathering profiles." Journal of the Geological Society of India 63(5): 545-550.

Negrel, P., H. Pauwels, et al. (2011). "Understanding groundwater systems and their functioning through the study of stable water isotopes in a hard-rock aquifer (Maheshwaram watershed, India)." Journal of Hydrology 397(1-2): 55-70.

Perrin, J., C. Mascre, et al. (2011a). "Solute recycling: An emerging threat to groundwater quality in southern India?" Journal of Hydrology 398(1-2): 144-154.

Perrin, J, Shakeel A., Hunkeler D. (2011b) "The effects of geological heterogeneities and piezometric fluctuations on groundwater flow and chemistry in a hard-rock aquifer, southern India" Hydrogeology Journal, (19-6): 1189-1201.

Pettenati, M., Perrin, J., Pauwels, H., Ahmed, S. (2012) Simulating fluoride evolution in groundwater using a reactive multicomponent transient transport model: application to a crystalline aquifer of Southern India. Applied Geochemistry. Accepted with minor revision.

Purushotham, D., M. R. Prakash, et al. (2011). "Groundwater depletion and quality deterioration due to environmental impacts in Maheshwaram watershed of R.R. district, AP (India)." Environmental Earth Sciences 62(8): 1707-1721.

Purushotham, D., A. N. Rao, et al. (2011). "Environmental impact on groundwater of Maheshwaram Watershed, Ranga Reddy district, Andhra Pradesh." Journal of the Geological Society of India 77(6): 539-548.

Sekhar, D. C., D. J. Reddy, et al. (2008). Ecology and management of red spider mite, Tetranychus urticae Koch on grape. Proceedings of the International Symposium on Grape Production and Processing. P. G. S. I. S. S. S. D. Adsule: 335-342.

Sreedevi, P. D., S. Ahmed, et al. (2006). "Association of hydrogeological factors in temporal variations of fluoride concentration in a crystalline aquifer in India." Environmental Geology 50(1): 1-11.

Sreekanth, P. D., N. Geethanjali, et al. (2009). "Forecasting groundwater level using artificial neural networks." Current Science 96(7): 933-939.

Sreekanth, P. D., P. D. Sreedevi, et al. (2011). "Comparison of FFNN and ANFIS models for estimating groundwater level." Environmental Earth Sciences 62(6): 1301-1310.